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THE WORKING, HEAT TREATING, AND WELDING OF STEEL

BOOKS BY H. L. CAMPBELL

METAL CASTINGS
318 pages. 6 by 9. 174 figures.

THE WORKING, HEAT TREATING, AND WELDING OF STEEL
Second Edition. Supplemented with a series of laboratory assignments. 230 pages. 6 by 9. 133 figures.

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THE WORKING, HEAT TREATING, AND WELDING OF STEEL

SUPPLEMENTED WITH A SERIES OF LABORATORY ASSIGNMENTS

BY

HARRY L. CAMPBELL, M.S.

SECOND EDITION

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SECOND EDITION

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TO THE MEMORY OF

ERNEST B. PERRY, M.E.

PREFACE TO SECOND EDITION

The purpose of this textbook is to present in a concise way the principles and the practice relating to the working, heat treating, and welding of steel. In the first chapter, the reader is introduced to the steelmaking processes; then follow discussions on methods for testing steel, the chemical composition of steel, and the classification of steel. The characteristics of the physical constituents in steel are described, as well as the effects of temperature changes and mechanical working upon the grain size and the resulting properties of steel. The processes for working, heat treating, and welding steel receive considerable attention in the text. Because of the ever-increasing uses of steel products, and the tremendous waste due to corrosion, methods for protecting steel from atmospheric corrosion are reviewed in the last chapter. A series of laboratory assignments is appended to the text to serve as a guide for the laboratory instruction which is usually given as part of this course of study. Many of the operations used in industrial shop practice are included in the laboratory assignments.

This textbook has been planned to assist in the introductory study of certain prescribed phases of the metallurgy of steel. An attempt has been made to exclude all unnecessary terms and discussions which rightfully belong to more advanced studies of these topics. The author recommends that other books be used to supplement this introductory treatise on steel, and to assist in the selection of supplementary reading, a list of titles of books on the metallurgy of steel is given on page 190.

During the preparation of the first edition of this textbook, the author obtained the valuable assistance of Professor C. Upthegrove, Professor O. W. Boston, Assistant Professor W. A. Spindler, and William Telfer of the University of Michigan. Furthermore, the author is greatly indebted to Assistant Professor W. A. Spindler of the University of Michigan, to Assistant Professor H. S. Jerabek of the University of Minnesota, and to James E. Campbell for their assistance during the rewriting of the text for the second edition. Manufacturers of equipment have kindly contributed information and illustrations.

H. L. Campbell

Omaha, Nebraska
August, 1940

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THE WORKING, HEAT TREATING, AND WELDING OF STEEL

CHAPTER I

THE DEVELOPMENT OF IRON AND STEEL PRODUCTS

THE MANUFACTURE OF WROUGHT IRON—**Puddling Process—Aston Process**—THE STEEL-MAKING PROCESSES—**Open-Hearth Process—Bessemer Process—Electric-Furnace Process**—Electric-Arc Furnace—High-Frequency Induction Furnace—**Crucible Process**—STEEL INGOTS

All iron and steel products are derived originally from pig iron, which is the raw material obtained from the reduction of iron ore in blast furnaces. A blast furnace has a circular steel shell about 20 feet in diameter and 100 feet high with an inside lining of refractory brick. See Fig. 1. The iron ore, limestone, and coke used in making pig iron are carried separately in small cars to a hopper at the top of the furnace. These materials pass from the hopper into the furnace through two bell-shaped valves which are opened and closed alternately to prevent the hot gases from escaping through the hopper. A large volume of preheated air is introduced continuously through openings known as tuyeres in the lower part of the furnace. This air for the combustion of the coke is heated by passing intermittently through one of several large steel cylinders known as hot-blast stoves. The brickwork on the inside of the stoves is heated by the hot gases discharged from the top of the blast furnace.

The process of reduction of iron ore to pig iron is known as **smelting.** The ores are essentially oxides of iron with varying proportions of foreign materials or gangue. The combustion of the coke in the lower part of the blast furnace furnishes the heat and reducing gases which bring about the reduction of the ore at a sufficiently high temperature to melt the resulting iron. The lime, produced from the limestone at the high temperatures within the furnace, combines with the gangue in the ore and the ash from the fuel to form a liquid slag.

Molten iron is removed at intervals of 4 to 6 hours through a tap

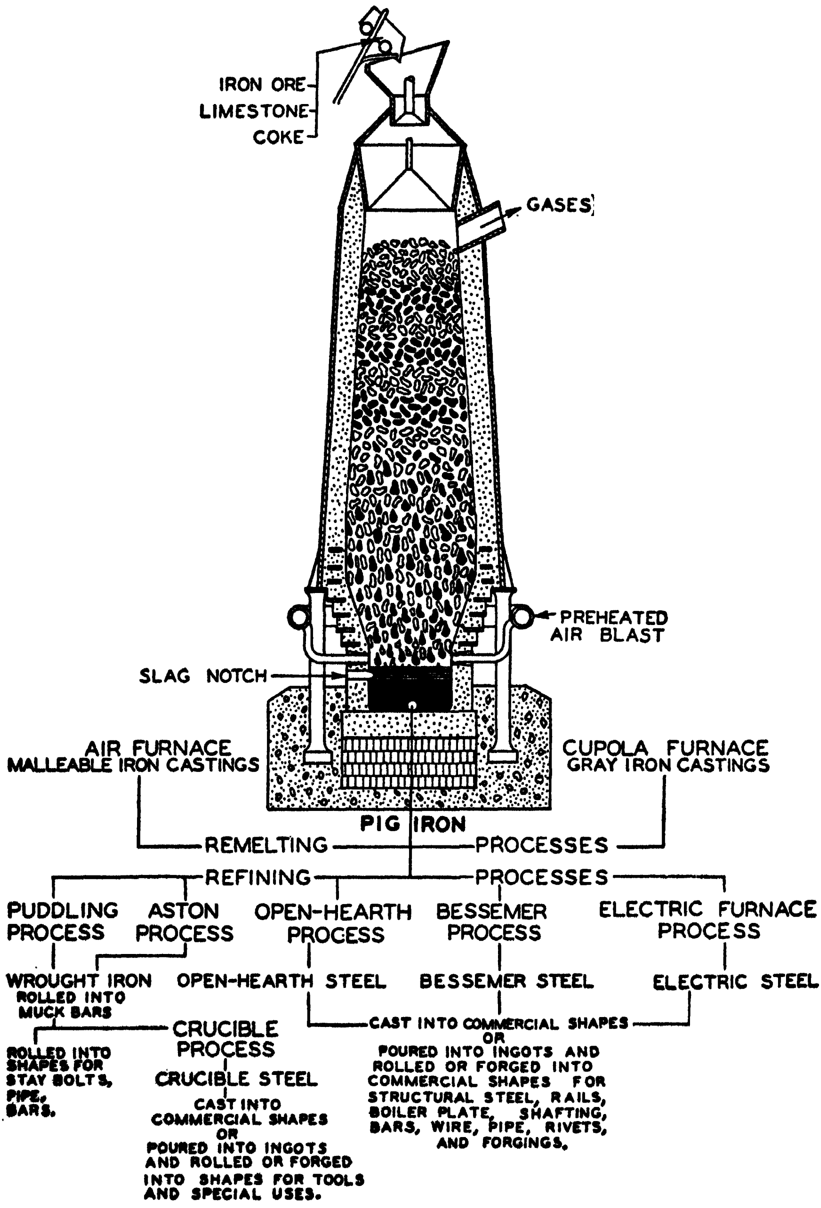

IRON ORE
LIMESTONE
COKE
GASES
PREHEATED AIR BLAST
SLAG NOTCH
AIR FURNACE
MALLEABLE IRON CASTINGS
CUPOLA FURNACE
GRAY IRON CASTINGS
PIG IRON
REMELTING PROCESSES
REFINING PROCESSES
PUDDLING PROCESS
ASTON PROCESS
OPEN-HEARTH PROCESS
BESSEMER PROCESS
ELECTRIC FURNACE PROCESS
WROUGHT IRON ROLLED INTO MUCK BARS
OPEN-HEARTH STEEL
BESSEMER STEEL
ELECTRIC STEEL
ROLLED INTO SHAPES FOR STAY BOLTS, PIPE, BARS.
CRUCIBLE PROCESS
CRUCIBLE STEEL
CAST INTO COMMERCIAL SHAPES OR POURED INTO INGOTS AND ROLLED OR FORGED INTO SHAPES FOR TOOLS AND SPECIAL USES.
CAST INTO COMMERCIAL SHAPES OR POURED INTO INGOTS AND ROLLED OR FORGED INTO COMMERCIAL SHAPES FOR STRUCTURAL STEEL, RAILS, BOILER PLATE, SHAFTING, BARS, WIRE, PIPE, RIVETS, AND FORGINGS.

FIG. 1—BLAST FURNACE AND DEVELOPMENT OF IRON AND STEEL PRODUCTS

hole at the bottom of the furnace, and the liquid slag which collects above the metal is drawn off through the slag notch located just below the tuyeres. The iron is cast into separate pieces known as pigs, which weigh about 50 pounds. While the iron is in the furnace it picks up 3 to 4 per cent of carbon and a small amount of sulphur from the coke. The silicon, manganese, and phosphorus as well as most of the sulphur in the pig iron are derived from the ore. See Table I. The average production of pig iron from one blast furnace is 600 tons in 24 hours.

TABLE I

CHEMICAL COMPOSITIONS OF IRON AND STEEL PRODUCTS

Material	Carbon %	Silicon %	Manganese %	Sulphur %	Phosphorus %
Pig Iron..........	3.00–4.00	0.50–3.50	0.50–2.00	0.02–0.10	0.03–1.00
Gray Cast Iron....	2.50–3.75	1.00–2.50	0.50–1.00	0.06–0.12	0.10–1.00
Malleable Cast Iron	2.00–2.50	0.50–1.10	0.20–0.30	0.04–0.06	0.10–0.20
Ingot Iron........	0.01–0.02	0.005	0.01–0.02	0.02–0.03	0.005
Wrought Iron.....	0.02–0.08	0.10–0.20	0.02–0.10	0.02–0.04	0.05–0.20
Carbon Steel......	0.05–1.50	0.05–0.30	0.30–1.00	0.02–0.20	0.02–0.15

The commercial iron products are cast iron, wrought iron, ingot iron, and steel. Refer to the outline in Fig. 1. Cast iron is obtained by remelting pig iron and casting the metal in the desired shapes. In the iron foundry, the metal mixtures are prepared by selecting the pig iron and scrap metals which will produce the desired chemical composition in the castings. The metal for gray iron castings is commonly melted in a cupola furnace. In the process for making malleable iron castings, the metal mixtures are generally melted in air furnaces, and the castings are heat treated to develop some ductility in the metal. The chemical compositions of the different forms of iron and steel are listed in Table I. The carbon and silicon in pig iron, gray cast iron, and malleable cast iron are much higher than in the other products. The difference in composition of wrought iron and low-carbon steel is chiefly in the manganese content.

Ingot iron, wrought iron, and steel are produced by refining processes which bring about the oxidation and removal of the carbon, silicon, and manganese from pig iron. The amounts of phosphorus and sulphur may also be decreased in the refining processes. The characteristic qualities of these refined products are a result of the manufacturing processes by which they are produced. Ingot iron is the purest of the commercial forms of iron. Wrought iron is similar in composition to ingot iron, except that wrought iron purposely contains a small proportion of slag. Steel differs from ingot iron in that the manganese and usually the carbon and silicon contents of steel are increased by furnace or ladle additions after the refining process.

Steel and ingot iron are in a molten state when they are finished in the furnaces, hence the slag which was formed during the refining period collects above the molten metal. On the other hand, wrought iron is in a pasty condition when its refining has been completed, and for this reason is mechanically mixed with a certain amount of slag, most of which is removed during subsequent steps in its manufacture.

THE MANUFACTURE OF WROUGHT IRON

Wrought iron is a highly refined iron with which is incorporated as much as 3 per cent of slag. After the wrought iron has been squeezed and rolled, the slag is present as microscopic strings or fibers which lie in the direction in which the bar was rolled. The non-corrosive slag constituent causes wrought iron to be resistant to progressive corrosion. Furthermore, the strings of slag produce a structure which lessens the effect of fatigue caused by vibration or shock. Wrought iron is well suited for forge welding because of the purity of the base metal and the fluxing action of the slag. Pipe and pipe fittings, plates, sheets, and bars are the principal forms in which wrought iron is used. Wrought iron is produced by two commercial methods known as the puddling process and the more recently developed Aston process.

Puddling Process

In the puddling process, a charge of about 500 pounds of pig iron and iron scrap is melted and refined in a puddling furnace. The combustion of bituminous coal on grates at one end of this furnace furnishes the heat for melting and refining the charges. During the refining period, the oxidation of silicon, manganese, and carbon is brought about by reactions with iron oxide which covers the bottom of the hearth. The removal of these elements during the process causes the melting temperature of the resulting metal to rise. As the temperature within the furnace is not sufficiently high to completely melt the refined iron, the metal becomes pasty, and is removed from the furnace in a plastic mass known as a puddle ball. Much of the entrained slag in the puddle ball is removed by a squeezing operation. The hot metal is then rolled into flat bars called **muck bars**, or **puddle bars**, which have a cross section of approximately $\frac{5}{8}$ by 4 inches. These bars are cut into short lengths, fastened together in piles, reheated to a welding temperature, and again rolled into bars. This procedure brings about the further removal of slag from the iron. When the operations of cutting, piling, reheating, and rolling are repeated a second time, the product is known as **double-refined iron.**

Aston Process

The Aston process for producing wrought iron requires the melting of pig iron in a cupola furnace and then refining the molten iron in a Bessemer converter. At the same time, a quantity of iron silicate slag is prepared in an open-hearth furnace. The refined iron is poured at a predetermined rate into a ladle containing the molten slag. As the temperature of the slag is maintained several hundred degrees lower than the freezing point of the refined metal, the latter is rapidly solidified. Gases are liberated during the solidification period and the metal is divided into small globules which form a spongy mass on the bottom of the ladle. This operation is known as **shotting.** After the excess slag is poured from the ladle, the remaining mass of refined iron and slag, weighing about 6,000 pounds, is transferred to a press where some slag is removed. The rectangular block formed in the press is known as a **bloom.** The hot bloom is immediately passed through rolling mills where it is reduced to the shapes and sizes required for commercial uses.

THE STEEL-MAKING PROCESSES

Steel is an alloy chiefly of iron and carbon produced completely in the liquid state by refining pig iron. All steels are ductile at some temperature in the condition as cast. The commercial processes for making steel are (1) open-hearth, (2) Bessemer, (3) electric furnace, and (4) crucible.

The relative importance of the steel-making processes may be seen from the following records of the *Bureau of Mines* on the production of steel in the United States during 1938: basic open-hearth steel 25,691,963 gross tons; acid open-hearth steel 272,337 gross tons; Bessemer steel 1,880,661 gross tons; electric furnace steel 505,024 gross tons; and crucible steel 6 gross tons. These records show that, on the basis of tonnage of steel produced, the basic open-hearth is by far the most important commercial process.

Open-Hearth Process

In the open-hearth process for producing steel, pig iron and steel scrap are melted and refined on a hearth by heat from the combustion of gaseous fuel. In some operations, molten iron from a blast furnace is used in the open-hearth furnace. The furnace shown in Fig. 2 has a shallow hearth surrounded by a roof and walls of refractory brick. To obtain the high temperatures required in this furnace, the gaseous fuel and air are preheated by passing through chambers known as regenerators located at each end of the furnace and are burned in the space above the hearth. The products of combustion pass over the entire length of the hearth and finally heat the brickwork in one set of regenerators before passing to the stack. At regular intervals, the direction of the flow of the gases is changed so that one set of regenerators is being heated by the gases leaving the furnace while the other set is being used to heat the gases which enter the furnace.

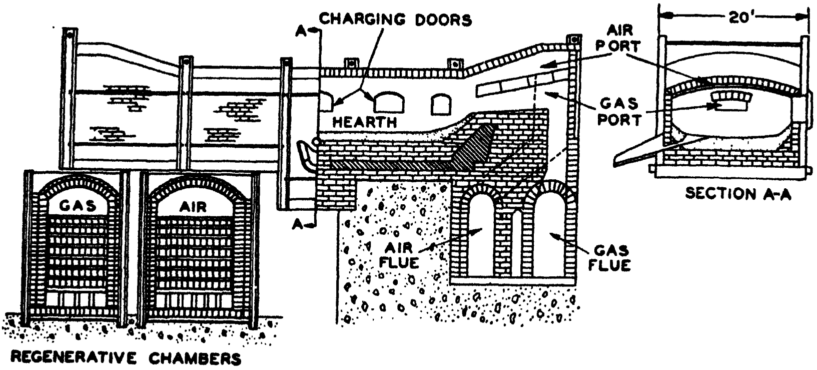


Fig. 2—Open-Hearth Furnace

The two modifications of open-hearth operations are designated as acid practice and basic practice. The difference lies in the nature of the slags used on the bath of metal and therefore the types of furnace linings which must be used to resist attack by these slags. In **acid practice**, a lining of silica sand is fused on the hearth and an acid slag (high in silica, SiO_2) is produced on the metal during the refining period. As it is not possible to remove phosphorus and sulphur in acid open-hearth practice, the pig iron and steel scrap used in the furnace charges must be low in these elements. The refining of the metal is accomplished by reactions with a slag rich in iron oxide. The silicon and manganese in the metal become oxidized by the iron oxide, and collect in the slag. Carbon is also oxidized and passes off as a gas. At the end of the refining period ferro-alloys are added to remove excess oxides from the metal and to produce the desired composition in the steel.

In **basic practice**, limestone is charged with the pig iron and steel scrap, and a basic slag (high in lime, CaO) is formed on the bath after the metal melts. The hearth of the basic furnace is lined with a mixture of burned magnesite (MgO) and basic open-hearth slag. Most of the phosphorus and some sulphur are taken up by the basic slag. In this practice, silicon, manganese, and carbon are eliminated by reactions with iron oxide in the slag. After the metal has been sufficiently refined, ferro-alloys are added to deoxidize the metal and to obtain the desired proportions of silicon, manganese, and carbon. A total time of 8 to 10 hours is required to melt and refine the average charge of 100 tons of open-hearth steel.

Ingot iron is produced in the basic open-hearth furnace by a process similar to that used in making steel. The materials used in the furnace charges are selected to have the impurities as low as possible. Also, the refining practice is carried to an extent such that all elements other than iron are reduced to a minimum. As the purity of the metal increases, the melting point is raised, and it is, therefore, necessary to operate the open-hearth furnace at a considerably higher temperature when making ingot iron than when making steel. The highly refined iron containing less than 0.16 per cent total impurities is cast into ingots and later rolled into sheets and bars.

Bessemer Process

In the Bessemer process for making steel, air is blown through molten pig iron in a Bessemer converter. A converter, as shown in Fig. 3, is constructed of a steel shell lined with refractory material and supported on trunnions. Air at ordinary atmospheric temperature is supplied at a pressure of about 20 pounds per square inch through openings known as tuyeres in the bottom of the converter. Molten iron from a blast

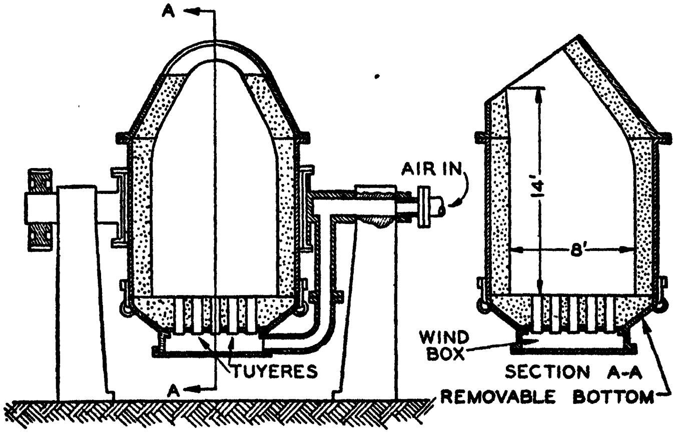


Fig. 3—Cross Section of Bessemer Steel Converter

furnace is poured into the converter while it is tipped to one side. The air is introduced through the tuyeres before the converter is turned to an upright position. When the air passes through the molten metal, it oxidizes some of the iron to form iron oxide (FeO), which in turn reacts with the silicon, manganese, and carbon in the metal. This combination of oxygen from the air with the elements in the molten metal produces a large amount of heat which maintains a high temperature in the resulting steel. The oxides of silicon and manganese collect in the slag, whereas the oxide of carbon passes off as a gas. At the end of the blowing period, practically all the silicon, manganese, and carbon have been removed from the metal which at this point contains considerable iron oxide and dissolved gases. Additions of ferro-alloys containing silicon, manganese, and carbon are made to the metal in the converter or as the metal is being poured from the converter. These alloys remove the undesirable oxides and gases from the metal, and at the same time supply the necessary proportions of the elements in the steel. The weight of metal which is blown at one time is about 25 tons, and the refining period requires 12 to 18 minutes.

Electric-Furnace Process

The electric furnace offers the advantage of obtaining high temperatures without introducing oxygen or nitrogen from the air, or impurities from the fuel. All operating conditions can be more readily controlled in this process than in any of the other steel-making processes. Two types of electric furnaces used in the manufacture of steel are the direct-arc furnace and the high-frequency induction furnace.

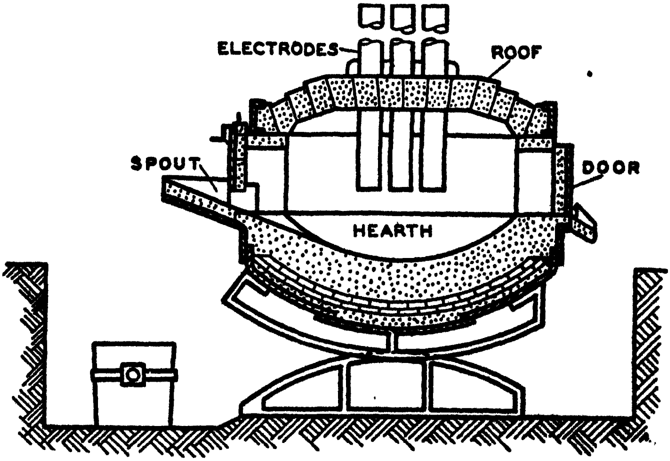
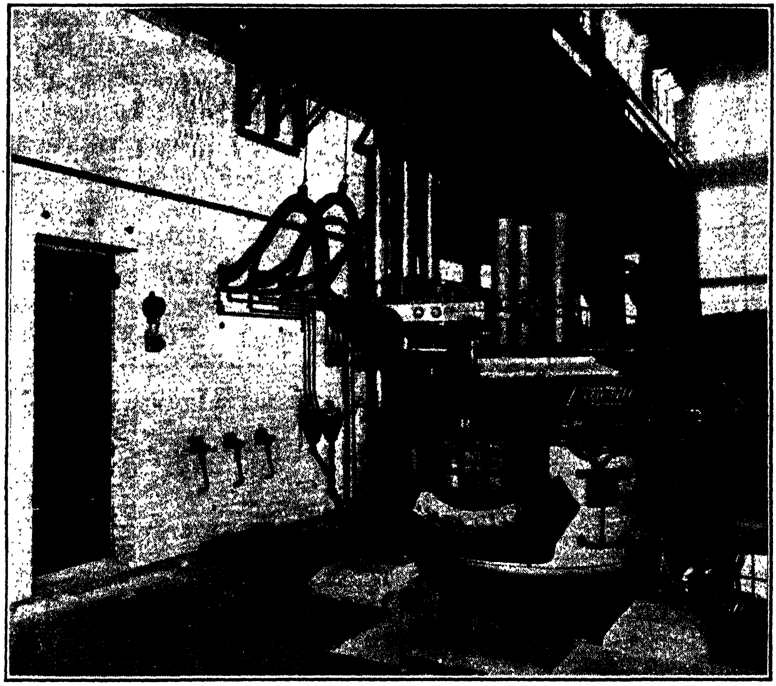


Fig. 4—Cross Section of Electric-Arc Furnace

Electric-Arc Furnace—This furnace, as shown in Fig. 4, is constructed of a heavy steel shell which is lined with refractories. The roof is built separately and can be replaced when necessary. A charging door is provided at one side of the furnace and a pouring spout is on the opposite side. This furnace is mounted so that it can be tilted for charging, slagging, or pouring. The three electrodes are supported in a vertical position above the hearth and extend through the roof. The electrodes are made of graphite or amorphous carbon. Connections are made from a three-phase alternating-current supply to the electrodes. Arcs are sprung from the electrodes to the metal on the hearth, thus heating the metal both by direct conduction from the arcs and by radiation from the roof and walls. When the furnace is in operation, the electrodes are raised and lowered by automatic controls to maintain the desired current as the electrodes become shorter or the level of the metal changes. The transformers and electrical control equipment are usually located in a separate room adjacent to the furnace. See Fig. 5.



Courtesy of Pittsburgh Lectromelt Furnace Corporation

FIG. 5—ELECTRIC-ARC FURNACE

Voltages between 90 and 200 are employed—the higher voltages for melting and the lower voltages for refining. Direct-arc furnaces are in use with capacities ranging from ½ to 100 tons of metal in each heat.

Steel is produced in electric-arc furnaces by melting cold charges, after which the metal is refined, or by refining metal which is supplied in the molten state from other furnaces. When it is necessary to purify the metal with the aid of basic slags, the hearth is lined with a basic refractory such as magnesite. Otherwise, an acid lining of silica brick and silica sand is used on the hearth.

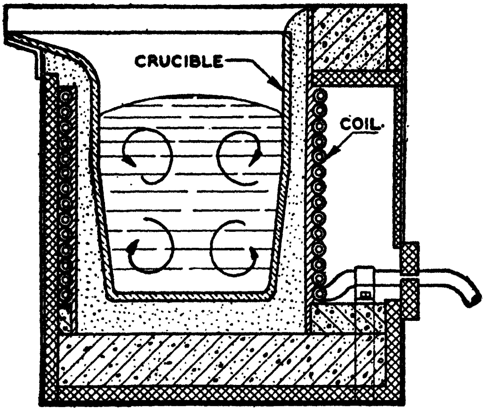


Fig. 6—Cross Section of Induction Furnace

Courtesy of Ajax Electrothermic Corporation

Fig. 7—High-Frequency Induction Furnace

High-Frequency Induction Furnace—The high-frequency induction furnace is essentially a crucible furnace in which the heat is developed by the resistance offered to an induced current within the metal charge. The construction of this furnace is shown in Fig. 6. When the furnace is in operation, the high-frequency current is passed through a coil of copper tubing which surrounds the crucible. This coil is the conductor for the high-frequency current which induces a much larger current through the metal contained in the crucible. This induced current heats the metal to a high temperature. Water is circulated through the tubing to lower the temperature of this conductor.

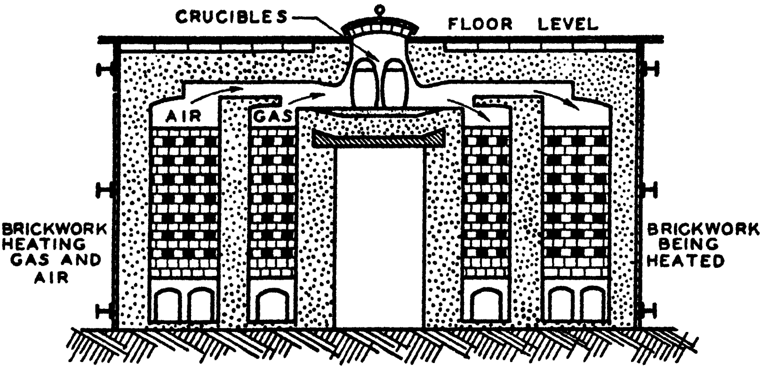


FIG. 8—CROSS SECTION OF FURNACE FOR MELTING STEEL IN CRUCIBLES

As soon as some of the metal is melted, a stirring action takes place, which insures thorough alloying of the materials within the crucible. The capacities of industrial high-frequency induction furnaces now in use range from 100 to 16,000 pounds of metal. These furnaces are supplied with current at 960 or 1,000 cycles from single-phase generators in units of 150 to 1,700 kilowatts output. A modern installation of a high-frequency induction furnace is illustrated in Fig. 7. This furnace is mounted on trunnions so that it can be tilted for pouring the steel into ladles or ingot molds.

Crucible Process

The crucible process consists of melting in closed crucibles properly proportioned mixtures of wrought iron, steel scrap, ferromanganese, and charcoal. Other ferro-alloys are added when alloy steel is produced by this process. After these materials are melted and thoroughly alloyed, the crucibles are taken from the furnace and the steel is poured into ingot molds. The ingots which are about 4 inches square are later rolled or forged to the desired shapes. The length of time between placing the crucible in the furnace and withdrawing the crucible for pouring is approximately 4 hours. This process is primarily a melting and alloying process, and no refining of the metal takes place in the crucible.

The crucibles hold 50 to 100 pounds of metal and are heated in gas-fired regenerative furnaces. A transverse section of a crucible furnace is shown in Fig. 8. The crucibles are made from a mixture of graphite, clay, and silica sand which has been moistened and mixed until it is of the proper consistency. After being formed to the desired shapes, the crucibles are dried and finally heated to high temperatures to harden the material. Steel produced by the crucible process costs more than steel made in larger heats by other processes. The use of crucible steel is, therefore, limited to special tools and other high-grade products.

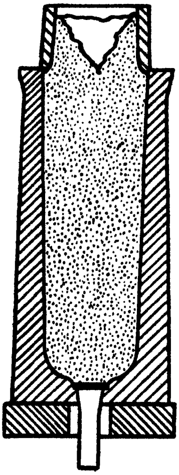


FIG. 9—SECTION OF INGOT IN BIG-END-UP MOLD WITH HOT TOP

STEEL INGOTS

As a rule, all the steel made at one time in a furnace is poured into a ladle provided with a nozzle in the bottom and a stopper to regulate the flow of metal from the ladle. The ladle is transferred to the pouring floor, where the steel is teemed into ingot molds. The cast-iron molds are usually square or rectangular in shape and are tapered to facilitate the removal of the ingots. The size of ingots varies with different practice, but ingots of low-alloy and carbon steels are often 6 feet high and 18 to 24 inches square with rounded corners. Ingots of tool steel and high-alloy steel are smaller in size.

As the metal in the ingot cools, solidification begins at the mold surface and continues towards the center of the ingot. During this period, the steel contracts and a cavity or pipe is left in the upper part of the ingot. When a refractory collar called a hot top is placed on the ingot mold, the steel is kept in the molten state longer at the top, hence the pipe is not as long as it would be otherwise. See Fig. 9.

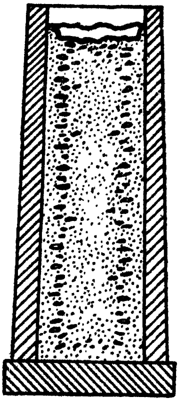


FIG. 10—SECTION OF INGOT OF RIMMING STEEL IN BIG-END-DOWN MOLD

The steel used in ingots is designated as killed, semi-killed, or rimming steel, depending upon the kind and amount of deoxidizers added before or during teeming. In general, all steels containing over 0.25 per cent carbon are killed or fully deoxidized. This condition is brought about by adding sufficient ferromanganese, ferrosilicon, aluminum, or other deoxidizers so that essentially no iron oxides remain dissolved in the steel and no gases are liberated during solidification. Semi-killed steels are only partially deoxidized, and the ingots made from these heats of steel may contain some gas cavities formed during solidification. Most steels with less than 0.15 per cent carbon are made by the rimming practice in which the steel is partially deoxidized with ferromanganese either alone or with some other deoxidizer. When this steel begins to solidify, the gas evolved cleanses the metal near the surface of the ingot, with the result that a layer of sound, clean metal is obtained. See Fig. 10. The large number of gas cavities in the interior of rimmed ingots must be welded shut in subsequent rolling operations. Steels for deep drawing are commonly made by the rimming process.

Courtesy of Republic Steel Company

FIG. 11—REMOVING INGOT FROM SOAKING PIT

After the ingots have cooled until the outside becomes solid, they are stripped from the molds and are placed in furnaces known as **soaking pits,** where they remain until the desired forging or rolling temperature is obtained throughout the entire ingots. The soaking pits are usually fired with gaseous fuel. From the soaking pits, the ingots are transferred to large presses, hammers, or rolling mills, where the steel is worked to pieces having the desired shapes and dimensions. Fig. 11 shows an ingot being removed from a soaking pit.

REVIEW QUESTIONS

1. Outline the smelting process for the manufacture of pig iron.
2. What are the differences in the chemical compositions of the commercial forms of iron?
3. Describe the Aston process for producing wrought iron.
4. Discuss the differences in acid open-hearth practice and basic open-hearth practice.
5. Explain the refining process used in making Bessemer steel.
6. Show on a drawing the construction of a direct-arc furnace.
7. What equipment is required for melting steel in the high-frequency induction furnace?
8. Account for the high quality of steel made in the high-frequency induction furnace.
9. State the average capacities of each of the four types of steel-making furnaces.
10. Outline the procedure for handling the metal from the steel-making furnace to the rolling mill.

CHAPTER II

THE PHYSICAL TESTING OF STEEL

TENSILE PROPERTIES--HARDNESS MEASUREMENTS—**Brinell Test—Rockwell Test—Scleroscope Test**--CONVERSION DATA—IMPACT TESTING —FATIGUE TESTING

The quality of steel is usually established on the basis of tensile properties and hardness. Other tests, however, are used in finding the strength of steel under compression, shear, or torsional loading. Furthermore, specimens of steel may be subjected to suddenly applied loads as in impact testing, or to many repetitions of loading as in fatigue testing.

The physical properties of steel are obtained to determine its suitability for different purposes. High tensile properties are necessary for some uses, whereas hardness and wear resistance are required for other applications. Physical tests are also used to measure the effects of heat treatment or mechanical working to which the steel has been subjected, thereby assisting in the control of manufacturing processes.

The selection and preparation of the material for test specimens should receive careful attention. In each investigation, the steel in the test specimen must have had the same thermal and mechanical treatments as the material which it represents. A record is usually kept of the exact location of the material from which the specimen was prepared. It is also important that all test specimens have the form and dimensions prescribed in standard specifications.

TENSILE PROPERTIES

The dimensions of standard tensile test specimens for bar stock as well as for plate material, as adopted by the *American Society for Testing Materials*, are given in Figs. 12 and 13. Two punch marks are made on each specimen to fix the desired gage length, and the diameter or cross section of each specimen within the gage length is measured before testing. The tensile test requires the application of gradually increasing axial loads to a standard test specimen until the specimen breaks.

With the testing machine illustrated in Fig. 14, the loads in tension are applied through screws driven by a train of gears connected to an electric motor. The tensile test specimen is gripped in the pulling head and in the top head of the machine. A test in compression is made with the specimen located between the pulling head and the weighing table. During the test, the weighing beam is kept in balance by turning the handwheel. The load on the specimen at any instant is indicated by the position of the poise on the calibrated beam and by the reading on the micrometer dial.

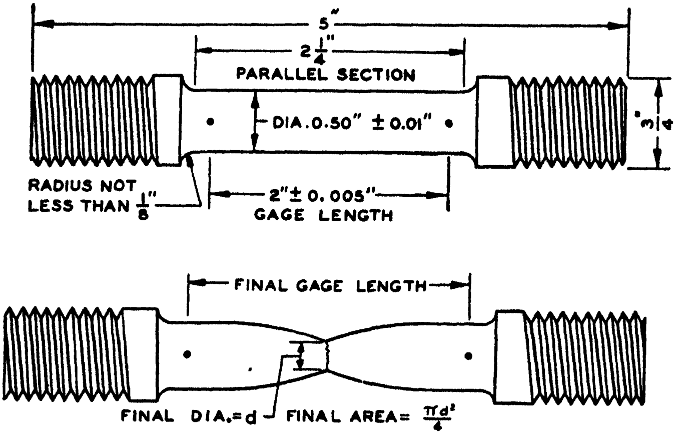


FIG. 12—TENSILE TEST SPECIMEN BEFORE AND AFTER TESTING (*A.S.T.M.* STANDARD)

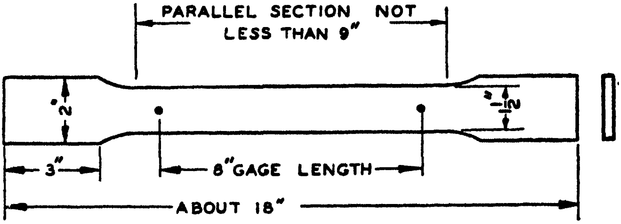


FIG. 13—TENSILE TEST SPECIMEN FOR PLATE MATERIAL (*A.S.T.M.* STANDARD)

The loads on the testing machine shown in Fig. 15 are obtained by pumping oil into a cylinder, thus applying pressure against a piston which is attached to the head of the machine. The tensile specimen is mounted between the upper movable head and the lower stationary head on the machine. A pressure gage calibrated in pounds indicates the load on the specimen.

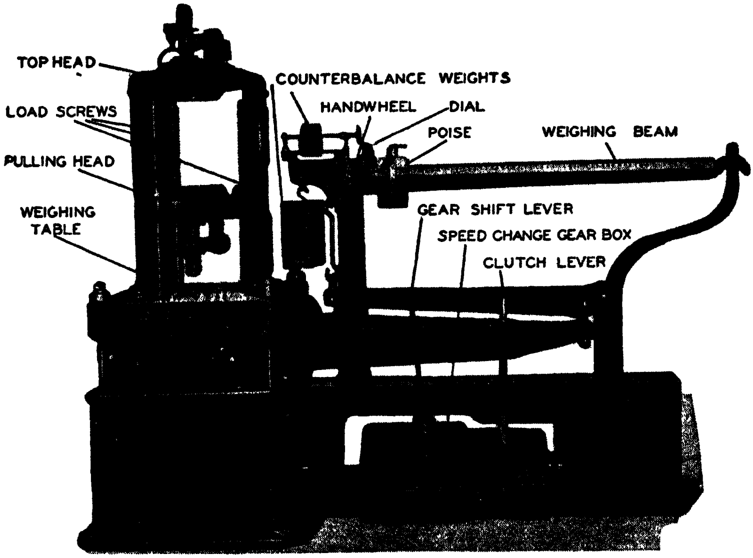
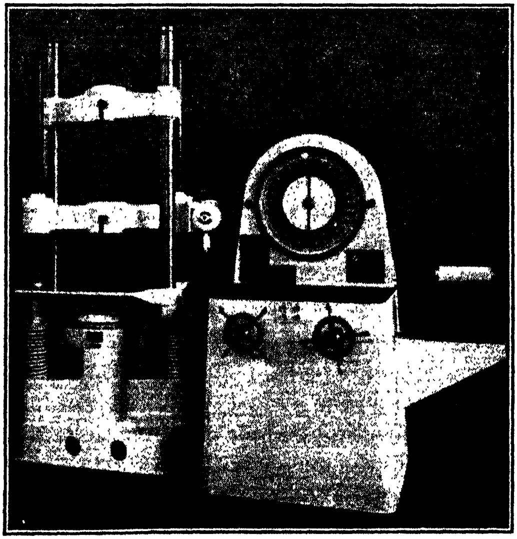


FIG. 14—UNIVERSAL TESTING MACHINE (SCREW-TYPE)



Courtesy of Baldwin-Southwark Corporation

FIG. 15—UNIVERSAL TESTING MACHINE (HYDRAULIC TYPE)

When a specimen of steel is subjected to increasing loads in tension, the elongation within the gage length is directly proportional to the applied loads up to a certain limit beyond which the metal elongates at a more rapid rate. The load per unit of the original area of the specimen at which this change in the ratio of the load to the elongation occurs is known as the **proportional limit.** To measure the small increments in the gage length of a tensile test specimen, an instrument known as an extensometer is attached to the specimen. If accurate readings are taken of the changes in gage length corresponding to different loads, and the data are plotted, a graph similar to the one shown in Fig. 16 will be obtained for a soft, ductile steel. The proportional limit is obtained from the graph where it changes from a straight line.

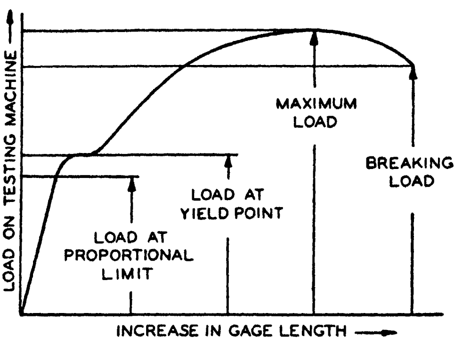


FIG. 16—LOAD-DEFORMATION DIAGRAM FOR TENSILE TEST

The **elastic limit** is a property of steel which is defined as the greatest load per unit of area of the test specimen which will not produce a measurable permanent elongation after the load is completely released. This property can be determined only by applying and releasing increasing loads until a permanent elongation is detected in the gage length. Because of the difficulty of this testing procedure, the elastic limit is not often obtained. However, the value of this property will usually lie between the proportional limit and the yield point.

As the stretching of the specimen is continued past the proportional limit, a point is reached at which the steel continues to elongate without an increase in load. This is the **yield point,** which is defined as the load per unit of the original area of the specimen at which a marked increase in the rate of elongation takes place. The yield point is usually detected by the drop of the beam on the screw-type testing machine or by a sudden halt of the load-indicating pointer on a hydraulic testing machine. A pair of dividers held in the punch marks on the test specimen may be used to determine the instant that a decided increase in the gage length takes place. The yield point is commonly assumed to be a measure of the maximum useful strength of a material.

$$\frac{\text{Yield Point}}{\text{Pounds per Square Inch}} = \frac{\text{Load on Specimen in Pounds at Yield Point}}{\text{Original Area of Specimen in Square Inches}}$$

For any metal which does not have a definite yield point, a property known as **yield strength** is determined to establish the maximum useful strength of the material. This property is defined as the maximum load per unit of the original area of the specimen that can be applied without causing more than a specified set; a set of 0.20 per cent of the gage length is often used for metals. The value of the yield strength is found on the diagram in Fig. 17 by drawing a line *M–N* parallel to the straight portion of the curve *O*-*A* at a distance away, *O–M*, equal to the specified set. The point of intersection, *N*, with the curve indicates the yield strength.

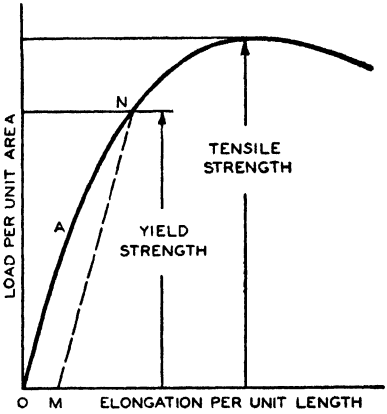


FIG. 17—UNIT LOAD—UNIT-ELONGATION DIAGRAM FOR TENSILE TEST

The **tensile strength** in pounds per square inch is computed by dividing the maximum load in pounds on the specimen by its original cross-sectional area in square inches. As increasing loads are applied to the specimen, the cross-sectional area is reduced. For all ductile steels, the breaking load is less than the maximum load, as shown on the diagram in Fig. 16.

$$\frac{\text{Tensile Strength}}{\text{Pounds per Square Inch}} = \frac{\text{Maximum Load on Specimen in Pounds}}{\text{Original Area of Specimen in Square Inches}}$$

The ductility of steel is determined by the percentage elongation and reduction of area of a tensile test specimen after failure. Sometimes the percentage elongation alone is used to indicate the ductility of metals. This property is found by measuring the distances between the two punch marks on the tensile test specimen before testing and after breaking. The difference in these lengths divided by the original gage length and multiplied by 100 gives the percentage elongation of the material.

$$\frac{\text{Elongation}}{\text{Per Cent}} = \frac{\left\{\begin{matrix}\text{Length between Gage}\\ \text{Points in Inches}\\ \text{After Breaking}\end{matrix}\right\} - \left\{\begin{matrix}\text{Original Length}\\ \text{between Gage}\\ \text{Points in Inches}\end{matrix}\right\}}{\text{Original Length between Gage Points in Inches}} \times 100$$

The metal in a tensile test specimen decreases in area during the test. Some steels will "neck down" considerably in the section near the fracture as illustrated in Fig. 12. The difference between the original cross-sectional area and the smallest cross-sectional area of the tensile test specimen after failure is the reduction of area. This property is usually expressed as a percentage of the original cross-sectional area. Heat-treated alloy constructional steels usually have a large reduction of area, whereas this property is relatively low in brittle steels.

$$\begin{array}{c}\text{Reduction of Area}\\ \text{Per Cent}\end{array} = \frac{\left\{\begin{array}{c}\text{Original Cross-}\\ \text{Sectional Area}\\ \text{of Specimen}\\ \text{in Square}\\ \text{Inches}\end{array}\right\} - \left\{\begin{array}{c}\text{Area of Specimen}\\ \text{in Square Inches}\\ \text{at Smallest Section}\\ \text{after Breaking}\end{array}\right\}}{\begin{array}{c}\text{Original Cross-Sectional Area of Specimen}\\ \text{in Square Inches}\end{array}} \times 100$$

When steel is subjected to any stress in tension less than the elastic limit, the increase in length is in direct proportion to the load applied. On removal of the load, the steel will return to its original dimensions. The changes in dimensions at stresses below the elastic limit are known as **elastic deformation** and the range of stress up to the elastic limit is known as the **elastic range.** The allowable working stress for steel parts is usually less than the elastic limit (or yield point) because at loads beyond this point the steel will remain permanently deformed. In the cold forming of steel, the metal is subjected to stresses higher than the yield point but less than the tensile strength of the material. This range of stress is known as the **plastic range** and the changes in dimensions are known as **plastic deformation.**

Bend tests are often required in specifications for constructional steels. The dimensions and surface condition of the specimens as well as the minimum extent of bending are usually stated. This test method is a measure of the ductility of the steel.

HARDNESS MEASUREMENTS

Hardness is a property which may be interpreted in two ways: resistance to indentation and resistance to abrasion. These two kinds of hardness are somewhat related, although a metal may be very hard in one sense and less hard in the other. The test methods for the measurement of hardness of metals are usually based on the resistance of the material to indentation. However, the resistance to abrasion can be determined by subjecting specimens of steel to definite abrasive conditions and measuring the resulting loss of metal; this procedure is known as wear testing.

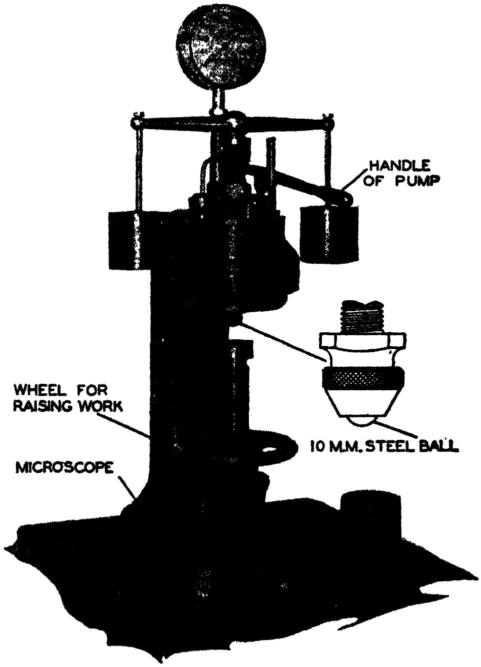
A file of good quality serves as a convenient means for establishing the relative hardness of hardened steel. In making this test, a sharp file is moved slowly but firmly across the object being tested. If the material resists the cutting action of the file, it is said to be "file hard." The upper limit in hardness of steel which can be filed is about Rockwell C-60.

The most widely used methods for measuring the hardness of steel are those employing the Brinell testing machine, the Rockwell hardness tester, and the Shore scleroscope. Each of these methods will be described. It is desirable to have the surfaces of the work smooth, and free from scale and decarburized metal, before making a hardness test. It is also important that the work be mounted in a horizontal position in the testing apparatus.

Brinell Test

In the Brinell test, a hardened steel ball 10 millimeters in diameter is forced into the specimen, under a load of 3,000 kilograms, for a period of at least 10 seconds. The diameter of the indentation formed on the specimen is then measured in millimeters with the aid of a microscope. The Brinell hardness number is the quotient obtained by dividing the applied load in kilograms by the spherical area of the impression in square millimeters. A list of Brinell hardness numbers with corresponding diameters of impressions is given in Table II.

A Brinell testing machine which is in general use for measuring the hardness of constructional steels is shown in Fig. 18. The object to be tested is placed on the anvil of the vertical threaded shaft and is raised in contact with the steel ball by turning the handwheel. To obtain the load required for this test, oil is pumped



Courtesy of Steel City Testing Laboratory

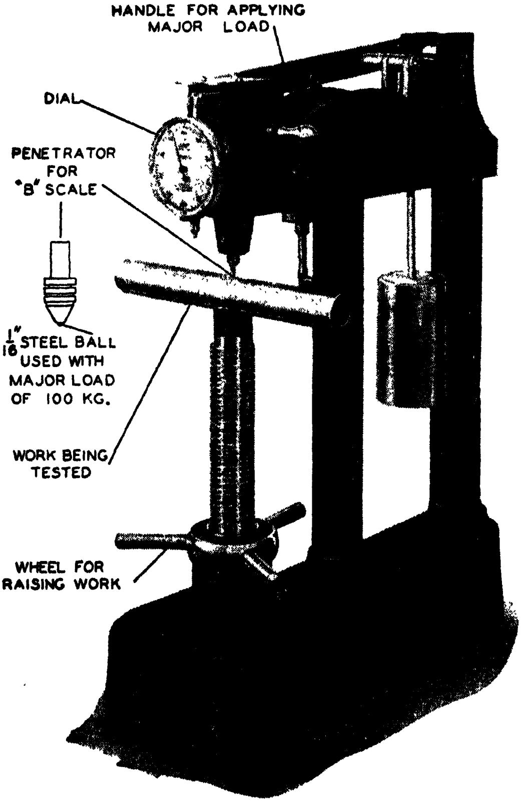
FIG. 18—BRINELL TESTING MACHINE

into a cylinder back of a piston to which the ball is attached. A pressure gage is provided to indicate the loads on the ball. The correct pressure for the test is maintained by a small relief piston carried on a horizontal arm to which weights are attached.

Specimens of soft steel which are to be tested with the Brinell machine should be at least 0.4 inch in thickness and the impressions should be taken at a sufficient distance from the edges of the specimens to avoid an uneven flow of the metal. Rounded surfaces should be ground flat before making Brinell tests.

Rockwell Test

The Rockwell test is used to measure hardness by determining, under an increment of load, the increment of depth of penetration of a steel ball or diamond cone into the material being tested. A preliminary load of 10 kilograms is first applied to a hardened steel ball $\frac{1}{16}$ inch in diameter, and then a major load of 100 kilograms is used. The Rockwell hardness readings are based on the depth to which the major load forces the steel ball below the depth to which it was impressed by the preliminary load. In the testing of very hard metals, a 120-degree diamond cone is used with a major load of 150 kilograms. A Rockwell hardness tester together with an enlarged view of a penetrator is illustrated in Fig. 19. This tester is employed widely for plant control and inspection purposes.

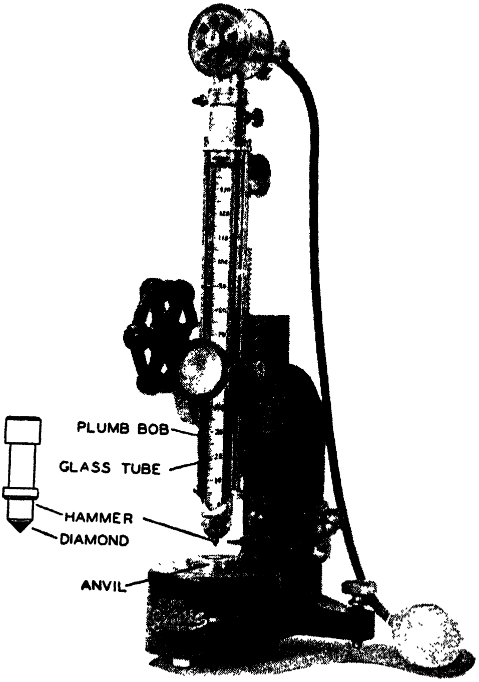

HANDLE FOR APPLYING MAJOR LOAD
DIAL
PENETRATOR FOR "B" SCALE
1/16" STEEL BALL USED WITH MAJOR LOAD OF 100 KG.
WORK BEING TESTED
WHEEL FOR RAISING WORK

Courtesy of Wilson Mechanical Instrument Company

Fig. 19—Rockwell Hardness Tester

The testing of hardened tool steel is commonly done with the diamond cone penetrator on the Rockwell tester.

The operation of the Rockwell tester is as follows: The work to be tested is placed on the anvil as shown in Fig. 19; the handwheel is turned to raise the work in contact with the penetrator until the pointer indicates that the minor load is applied; the bezel of the gage is turned to set the zero position on the dial behind the pointer; and the major load is then applied by moving the handle back. When the pointer comes to rest, the major load is released by moving the handle forward, and the Rockwell hardness number is indicated by the position of the pointer on the dial. The "B" scale on the dial is used for the steel ball penetrator, and the "C" scale for the diamond cone penetrator.



Courtesy of the Shore Instrument and Manufacturing Co.

FIG. 20—SHORE SCLEROSCOPE

Scleroscope Test

The hardness as measured by the Shore scleroscope is based on observations of the height of rebound of a diamond-tipped hammer which is allowed to fall through a fixed distance upon the polished surface of the material being tested. The hammer travels within a glass tube which is supported in a vertical position. The raising and releasing of the hammer are controlled by pressure on a rubber bulb. After each reading is taken, the specimen is moved so as to avoid having the hammer strike twice in the same spot. The hardness values are indicated on a scale graduated in arbitrary units from 0 to 140. The Shore scleroscope together with an enlarged view of a diamond-tipped hammer is shown in Fig. 20. This instrument is used commonly in the inspection of heat-treated steel parts. To obtain accurate readings, a clean, smooth surface should be prepared, and the foundation supporting the work should be as solid as possible. Because of its portability, the scleroscope can be used for measuring the hardness of large pieces of steel. Furthermore, hardness measurements can be made by this method without seriously marring the surfaces of finished steel parts.

CONVERSION DATA

The *Bureau of Standards* has published in Research Paper No. 185 the following formulas for converting Rockwell to Brinell numbers:

$$(1)\quad \text{Brinell number} = \frac{7{,}300}{130 - \text{Rockwell number (B scale)}}$$

(For Rockwell numbers greater than 40 and less than 100)

$$(2)\quad \text{Brinell number} = \frac{1{,}520{,}000 - 4{,}500\ \text{Rockwell number (C scale)}}{100 - \text{Rockwell number (C scale)}}$$

(For Rockwell numbers greater than 10 and less than 40)

$$(3)\quad \text{Brinell number} = \frac{25{,}000 - 10\ [57 - \text{Rockwell number (C scale)}^2}{100 - \text{Rockwell number (C scale)}}$$

(For Rockwell numbers greater than 40 and less than 70)

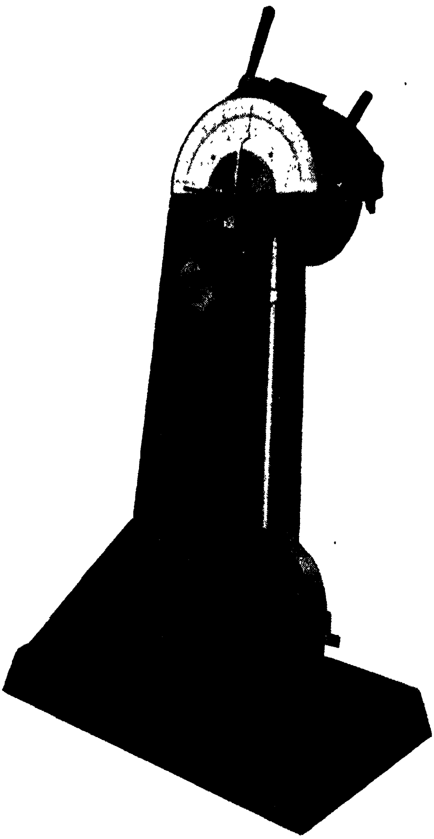
Although hardness values and tensile strengths for all steels are not definitely related, information giving the approximate relations between these properties is often useful. The comparative values of hardness and strength presented in Table II represent average conditions for heat-treated constructional alloy steels.

IMPACT TESTING

In determining the impact resistance of metals, a standard notched test specimen is broken by the impact of a pendulum hammer as the hammer swings through the lowest part of its arc. The energy consumed in breaking the specimen is measured by the height to which the hammer swings after breaking the specimen. A scale on the impact testing machine (see Fig 21) is adjusted so that the reading will be zero when the hammer moves freely from its starting position through the entire arc. When making an impact test, the pendulum hammer swings through a shorter arc after impact because part of its energy is consumed in breaking the specimen. The greater the resistance to impact of the test specimen, the greater will be the energy required to break the specimen, and the shorter will be the swing of the hammer. The energy consumed in breaking the notched specimen is indicated on the scale in foot-pounds.

The principal designs of impact specimens are shown in Fig. 22. The Charpy specimen which is supported at both ends in a horizontal position during the test is a square bar with a V or keyhole notch in one side. In the Izod test one end of the specimen is clamped in a vertical position between two jaws and the opposite end is struck by the pendulum hammer on the notched side.

No correlation has been found between the results of tests on notched impact specimens and the tensile strengths of steels. Furthermore, there does not appear to be a definite relationship between the results of impact tests and the fatigue life of a metal. This method of impact testing indicates only the notch sensitivity of material subjected to different thermal and mechanical treatments.



Courtesy of American Machine & Metals, Inc.

Fig. 21—Impact Testing Machine

A circular pendulum bob or hammer is attached to a rod which is mounted in bearings so that it can swing in an arc. Each impact specimen is mounted on the frame in a position which will allow it to be struck by the hammer. The arc through which the hammer swings after breaking the specimen is measured on the scale.

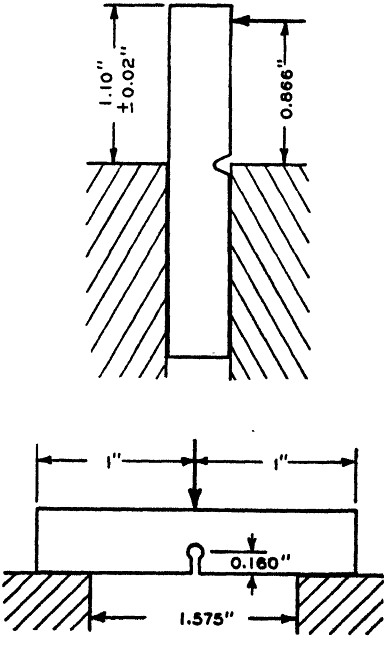


Fig. 22—Impact Specimens

FATIGUE TESTING

Failures of metal parts in service are often caused by the inability of the material to resist continuous repetitions of stress. When the load on a part is not uniformly distributed and the stress at some point is raised to an intensity beyond the tensile strength of the material, a crack starts at this location and, with repeated application of load, continues through the section. As the crack progresses, the remaining sound metal is gradually lessened until the part fails at a comparatively low load. Defects in the steel, sharp corners at intersections, holes, or rough surfaces may be the primary cause of fatigue failures. Fatigue may be defined as progressive failure started by excessive stress concentration and continued by many repetitions of loading.

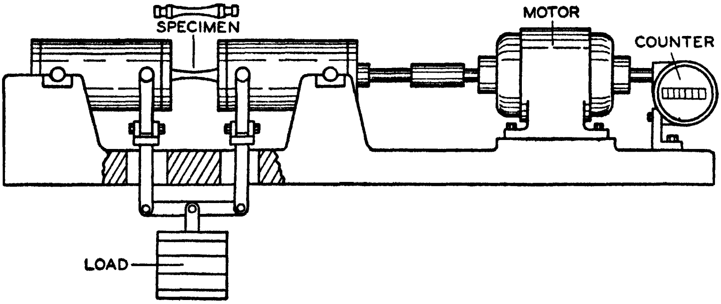


Fig. 23—Fatigue Testing Machine (R. R. Moore Design)

Tests to determine the fatigue properties of metals aim to establish the endurance limit of the metal and the effect of different factors on this value. The **endurance limit** is the maximum stress which can be applied repeatedly without causing failure. The rotating beam machine as shown in Fig. 23 is most commonly used for measuring the fatigue properties of metals. During the test, the specimen is rotated at a high speed and is subjected to a definite stress in tension and compression ranging from zero to a maximum with each revolution. A counter on the main shaft indicates the number of reversals of stress and stops automatically when the specimen fails. Many tests are required to establish the endurance limit of a material. As a rule, the endurance limit ranges from 40 to 60 per cent of the tensile strength of steel.

TABLE II
HARDNESS CONVERSION TABLE FOR ALLOY CONSTRUCTIONAL STEELS*

Brinell Test Diameter of Impression Millimeters with 3000 Kg. Load and 10-Mm. Ball	Brinell Hardness Numbers	Rockwell Hardness Numbers "C" Scale 150-Kg. Load and 120° Cone	Rockwell Hardness Numbers "B" Scale 100-Kg. Load and $\frac{1}{16}$-In. Ball	Shore Scleroscope Hardness Numbers	Approximate Tensile Strength in Units of 1000 Pounds per Square Inch
2.40	653	62	...	86	329
2.45	627	60	...	84	317
2.50	601	58	...	81	305
2.55	578	56	...	78	295
2.60	555	55	...	75	284
2.65	534	53	...	73	273
2.70	514	51	...	71	263
2.75	495	50	...	68	253
2.80	477	48	...	66	242
2.85	461	47	...	64	233
2.90	444	46	...	62	221
2.95	429	44	...	60	211
3.00	415	43	...	58	202
3.05	401	42	...	56	193
3.10	388	41	...	54	185
3.15	375	39	...	52	178
3.20	363	38	...	51	171
3.25	352	37	...	49	165
3.30	341	36	...	48	159
3.35	331	35	...	46	154
3.40	321	34	...	45	148
3.45	311	32	...	43	143
3.50	302	31	...	42	139
3.55	293	30	...	41	135
3.60	285	29	...	40	131
3.65	277	28	...	38	127
3.70	269	27	...	37	124
3.75	262	26	...	36	121
3.80	255	25	...	35	117
3.85	248	24	100	34	115
3.90	241	23	99	33	112
3.95	235	22	99	32	109
4.00	229	21	98	32	107
4.05	223	20	97	31	105
4.10	217	18	96	30	103
4.15	212	17	95	30	100
4.20	207	16	95	29	98
4.30	197	14	93	28	95
4.40	187	12	91	27	91
4.50	179	10	89	25	87
4.60	170	8	87	24	84
4.70	163	6	85	23	81
4.80	156	4	83	23	78
4.90	149	2	81	22	76
5.00	143	..	79	21	74
5.10	137	..	77	20	71
5.20	131	..	75	19	68
5.30	126	..	73	18	65

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* Data compiled by the Research and Development Department of The International Nickel Company. Reproduced by permission.

REVIEW QUESTIONS

1. What forms of loading are used in measuring the properties of steel?
2. Discuss the purposes for testing steel.
3. Outline the procedure for obtaining the tensile strength of the steel in a shaft 4 inches in diameter and 8 feet long.
4. State the method for finding the yield strength of cold-finished steel.
5. What computations are necessary for establishing the ductility of steel?
6. Account for the difference in the maximum load and breaking load in the tensile test of a low-carbon steel.
7. What are the three essential requirements of the method for obtaining Brinell hardness numbers?
8. Explain the principle of operation of the Rockwell hardness tester.
9. What are the advantages of the scleroscope method of hardness testing?
10. Find the approximate tensile strength of constructional alloy steel having a Brinell hardness number of 248.

CHAPTER III

THE CHEMICAL COMPOSITION OF STEEL

CARBON—MANGANESE—SILICON—SULPHUR—PHOSPHORUS

Steel is an alloy of iron and carbon together with other elements which are intentionally or unavoidably introduced into the metal during the manufacturing process. The properties of steel are dependent to a large extent upon the chemical composition of the metal. Therefore, an understanding of the influence of each of the chemical elements on the properties of steel is necessary in the selection of steel for definite purposes.

When steel is to be used in the condition as received from the mill, the mechanical properties of the material are most significant. In this case, the physical requirements are generally stated in the purchase specifications for the material. The specifications for steel proposed by the *American Society for Testing Materials* are based on its uses and include minimum physical properties as well as maximum limits for certain elements. On the other hand, steel which is to be heat treated, or is to undergo other treatment before being used, is purchased on the basis of chemical composition. The specifications of the *Society of Automotive Engineers* for steel (see Table III in Chapter IV) are based entirely on the chemical composition of the metal.

The composition of steel is determined by chemical analysis. The methods of analysis for many of the elements consist of dissolving a small sample of the steel in an acid solution, and then separating quantitatively certain compounds from the solution. Carbon is determined by passing oxygen gas over particles of the metal while heated to incandescence, and absorbing the carbon dioxide resulting from the combustion of the carbon. The proportions of the elements in the steel are finally calculated from these determinations. Standard methods of analysis of steel have been established by the *American Society for Testing Materials* and are available in the publications of the *Society*. The report of the chemical analysis gives the percentages of the elements in the steel with the exception of iron, which is assumed to make up the balance of the composition. It should be understood, however, that these chemical elements are not present in the pure state in the steel, but exist in combination with iron or with one another. The purpose of a chemical analysis of steel is to determine whether the percentages of the elements are within the limits which are regarded as satisfactory for its particular requirements. Because of the great variety of uses of steel, many different specifications have been adopted for this material. Those which have been most generally accepted have been prepared by the *American Society for Testing Materials* and the *Society of Automotive Engineers.*

The effects of the chemical elements on the properties of steel will now be described. Only those elements which in addition to iron are present in all carbon steels are included in this discussion. The special alloying elements such as nickel, chromium, molybdenum, tungsten, and vanadium will be considered in Chapter X.

CARBON

As a general rule, carbon has a greater influence on the mechanical properties of steel than any of the other elements. With an increase in carbon from 0.10 to 0.83 per cent, the tensile strength, yield point, and hardness become greater, whereas the percentage elongation and reduction of area are lowered. This relationship of carbon content to the tensile properties of hot-rolled carbon steels is shown on the curves in Fig. 24. Steels containing less than 0.60 per cent carbon are employed for constructional purposes which require a favorable combination of strength and ductility, whereas steels containing 0.60 per cent and higher carbon are selected for applications in which hardness and wear resis-

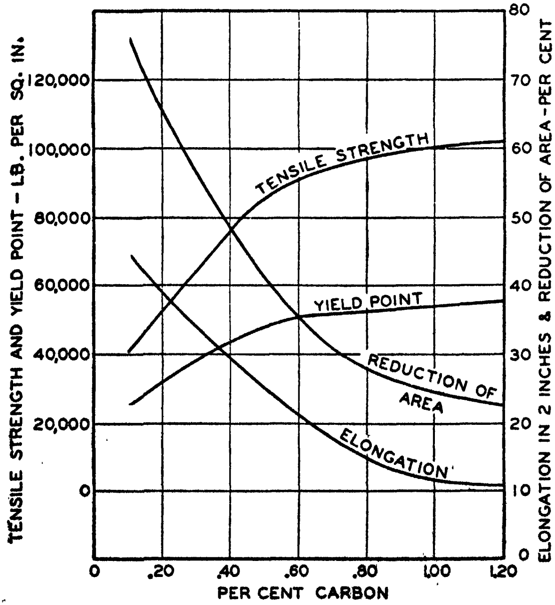

Fig. 24—Effect of Carbon Content on the Properties of Hot-Rolled Carbon Steels

tance are of great importance. Refer to Table IV in Chapter IV which gives the carbon ranges for different uses of carbon steels. Carbon occurs in steels in the combined state with iron or with other elements which form compounds. A wide range in the physical properties of steels is possible because of the influence of the carbon compounds in the metal.

MANGANESE

During the manufacture of steel, manganese serves as a valuable deoxidizing and purifying agent. This action is brought about by the uniting of the manganese with the dissolved oxygen in the molten metal, thus forming an oxide of manganese which collects in the slag. Manganese also combines with sulphur, and thereby decreases the harmful effect of this element remaining in the steel.

Manganese occurs in steel in solid solution with the iron, in chemical combination with iron and carbon, and to some extent as manganese sulphide. The manganese content of carbon steels is usually less than 1.00 per cent, and commonly ranges from 0.30 to 1.00 per cent. This element causes an increase in the tensile strength and is considered to be generally beneficial to steel.

SILICON

Silicon is particularly advantageous in the steel-making processes because of its deoxidizing and cleansing effects. The amount of silicon which remains in the finished steel usually ranges from 0.05 to 0.30 per cent. In these proportions, the silicon is dissolved in the iron, and has no appreciable effect on the physical properties of the steel.

SULPHUR

Sulphur occurs in steel either as iron sulphide, FeS, or as manganese sulphide, MnS. When iron sulphide is present, it forms a network at the grain boundaries of the steel. This constituent has a low melting point and causes a lack of cohesion between the grains of the steel when it is hot worked. The property of being weak at high temperatures is known as **hot shortness.** Manganese sulphide has a higher melting point than iron sulphide and does not liquefy at the temperatures used in hot working. Therefore, manganese sulphide is less objectionable in steel than iron sulphide. To insure that the sulphur will all be in the form of manganese sulphide, it is necessary to have the manganese about five times the sulphur content. In many specifications for constructional steels, the sulphur content is limited to 0.06 per cent. Steel which is used for tools usually has the sulphur below 0.04 per cent.

Steels containing sulphur in high percentages are readily machined because the sulphide inclusions interfere with the continuity of the metal and allow the chips to break up at the cutting tool. A grade known as **screw stock** has a sulphur content intentionally within the range of 0.07 to 0.30 per cent. This steel is generally made by the Bessemer process, and because of its high sulphur and high phosphorus (0.09 to 0.13 per cent phosphorus) is not satisfactory for applications requiring resistance to shock. The non-metallic inclusions in Bessemer screw stock cause a decrease in the ductility of the metal.

PHOSPHORUS

Phosphorus combines with iron and is present in solution in the steel. In low-carbon steels (maximum 0.15 per cent carbon), phosphorus raises the yield point and improves the resistance to atmospheric corrosion. The percentage of phosphorus in steels which must have favorable impact resistance is dependent upon the carbon content. The sum of the carbon and phosphorus usually does not exceed 0.25 per cent. In the *S.A.E.* specifications, phosphorus is held to a maximum of 0.045 per cent. Tool steels of the best quality do not contain more than 0.02 per cent phosphorus.

REVIEW QUESTIONS

1. What is the purpose of a chemical analysis of steel?
2. What are the limiting proportions of carbon in steel?
3. What are the effects of increasing carbon percentages on the tensile strength, elongation, and hardness of steel?
4. In what condition does carbon occur in steel?
5. What is the effect of manganese in the steel-making process?
6. What should be the percentage of manganese in carbon steels?
7. Discuss the importance of silicon in steel.
8. In what form is sulphur the least detrimental in steel?
9. What is the composition of Bessemer screw stock and its particular application?
10. What should be the limiting content of phosphorus in steel for tools?

CHAPTER IV

THE CLASSIFICATION OF STEEL

CLASSES BASED ON THE STEEL-MAKING PROCESS—**Open-Hearth Steel—Bessemer Steel—Electric-Furnace Steel—Crucible Steel**—CLASSES BASED ON THE COMPOSITION OF STEEL—**Carbon Steels—Alloy Steels—*S.A.E.* Classification**—CLASSES BASED ON THE GRAIN SIZE OF STEEL—CLASSES BASED ON THE USES OF STEEL—**Constructional Steels—Low-Carbon Steels—Medium-Carbon Steels—Tool Steels—*A.S.T.M.* Specifications**—CLASSES BASED ON THE CONDITION AND FORM OF STEEL—**Semi-Finished Steel—Finished Steel—Grades of Bar Steel**

Steel is made of many compositions by any one of four processes, and is marketed in different conditions and forms for a great variety of uses. It is well to understand the classification of the large number of types of steel which are now employed in all branches of industry. In general, steel may be classified according to its method of manufacture, its chemical composition, its grain size, its application, and the condition in which it is used. Complete specifications are necessary to indicate the desired characteristics of the steel for a specific purpose.

CLASSES BASED ON THE STEEL-MAKING PROCESS

Each steel-making process described in Chapter I yields metal having special characteristics. These differences in qualities should be considered when steel is being selected for definite requirements. The grades of steel obtained from each of the four steel-making processes will now be discussed.

Open-Hearth Steel

In the basic open-hearth process, phosphorus and sulphur can be removed from the metal, and, because of this provision, a good grade of steel can be obtained from low-priced melting stock. All the elements in the composition of this steel can be secured in the percentages desired. Basic open-hearth steel is supplied in structural shapes, rails, bars, sheets, and plates for many purposes. In fact, over 90 per cent of the steel produced in the United States is made in basic open-hearth furnaces.

Acid open-hearth steel is usually more free from foreign inclusions than basic open-hearth steel. For this reason, acid open-hearth steel is preferred for some uses where a superior grade is necessary. Armor plate and special wire for wire rope are made of acid open-hearth steel. As it is not possible to remove phosphorus and sulphur from the metal in acid open-hearth practice, the pig iron and steel scrap used in the furnace charges must be low in these elements. Because of the high cost of melting stock, acid open-hearth steel usually costs more than steel made by the basic open-hearth process.

Bessemer Steel

All Bessemer converters used in the United States are lined with acid refractories, and most of the steel made by this process contains phosphorus and sulphur in relatively large percentages. This steel can be machined more readily than other grades containing low phosphorus and sulphur. A large proportion of Bessemer steel is cold finished for industrial purposes. As a rule, carbon steels in the higher ranges of carbon and alloy steels are not produced by the Bessemer process. Most of the steel made by this process goes into bars for screw-machine products, strips for welded pipe, wire, sheets for tin plate, concrete reinforcing bars, and structural sections.

Electric-Furnace Steel

Electric steel-making furnaces are operated with either acid linings or basic linings. In the production of steel castings, the practice often consists of melting steel scrap of a good grade in an acid-lined electric furnace. Clean, sound steel can be made by this method. In the basic electric furnace, the steel can be purified to any extent desired. This condition together with the possibility of control of the furnace atmospheres and temperatures make this process well suited to the production of steels of high quality. Alloy steels for tools as well as for constructional purposes are made by the electric-furnace process.

Crucible Steel

Steel of high quality can be produced by the crucible process because relatively pure materials are used in its preparation, and there is little opportunity for contamination while it is being made. A very small amount of alloy tool steel is now made in crucibles.

CLASSES BASED ON THE COMPOSITION OF STEEL

Steel is ordinarily classified on the basis of its chemical composition into two main classes which include carbon steels and alloy steels.

These classes will now be defined and will be subdivided into other groups.

Carbon Steels

The carbon steels possess properties which are dependent primarily upon the carbon content. The range of carbon in commercial steels is from about 0.05 to 1.50 per cent. For convenience when referring to a general division of the carbon range, these steels may be separated into three groups, which are designated as **low-carbon steels** with carbon up to 0.30 per cent, **medium-carbon steels** within the limits of 0.30 to 0.60 per cent carbon, and **high-carbon steels** with the carbon content above 0.60 per cent. It should be recognized that these divisions are not sufficiently definite to be used when selecting steels to satisfy specific physical requirements.

Carbon steels may be classified further into plain carbon steels and special carbon steels. **Plain carbon steels** contain relatively small proportions of phosphorus and sulphur together with normal percentages of silicon and manganese. **Special carbon steels** often contain relatively large proportions of sulphur, and sometimes additional elements such as copper, which confer special characteristics upon the steel. Copper is added to steel in small amounts, usually less than 0.50 per cent, to improve its resistance to atmospheric corrosion. The presence of small percentages of copper in steel has little effect upon the strength or ductility of the metal within the lower ranges of carbon content.

When the sulphur content is increased over the amount which is normally present in plain carbon steels, the metal can be machined much more readily. This free-cutting property is caused by the lack of uniformity in the structure of the metal resulting from inclusions of manganese sulphide. Steel which has a high sulphur content can be machined at high speeds, and the chips produced break up and do not obstruct the cutting action of the tool. A number of free-cutting steels are available in commercial shapes and sizes. The steel designated as *S.A.E.* 1112 contains 0.10 to 0.20 per cent sulphur and 0.09 to 0.13 per cent phosphorus. This grade of steel when made by the Bessemer process is known as **Bessemer screw stock.** Several other analyses of high-sulphur steels are included in the *S.A.E.* specifications. See Table III. Another type of free-machining steel recently developed contains up to 0.25 per cent lead. The advantage of obtaining improved machinability by additions of lead is that other physical properties of the steel are not appreciably affected. These special carbon steels are particularly advantageous for the manufacture of parts made on automatic screw machines.

Alloy Steels

Alloy steels have special physical or chemical properties which are dependent upon the addition of metallic elements other than those present in carbon steels, or upon a considerable increase in either of the elements silicon or manganese. The chief alloying elements used in steel are nickel, chromium, molybdenum, vanadium, manganese, silicon, and tungsten. These elements may be used separately or in combinations to produce the desired characteristics in the steel. The influence of each of the alloying elements on the properties of steel is described in Chapter X.

All alloy steels may be classified in three general groups: first, those which are usually employed for constructional purposes in the condition as rolled; second, the large number of constructional alloy steels (refer to Table III) which are heat treated to develop the desired physical properties; and third, those steels, often containing high percentages of alloying elements, used for tools and dies as well as for corrosion- and heat-resisting purposes.

Some alloy steels are produced in structural sections, sheets, plates, and bars particularly for use in the condition as rolled. Higher physical properties and greater resistance to corrosion are obtained with these steels than are possible with hot-rolled carbon steels. These alloy steels are employed chiefly for structures in which strength per unit of weight is of special significance; such applications include bridge members, railroad cars, bodies for trucks and buses, and long booms for cranes.

Large quantities of alloy steels are used in the heat-treated condition for machine parts. The *S.A.E.* specifications (refer to Table III) include many different compositions of steels which are heat treated to develop the desired combinations of properties. The compositions, heat treatments, and properties of a number of alloy constructional and tool steels are given in Chapter X.

In the selection of alloy steels for definite applications, many factors should be considered such as: the cost and availability of the materials; the physical properties of the steels in the hot-rolled or cold-finished condition, or after suitable heat treatments; the ease of machining or other form of processing required; and the reactions with the atmosphere or other materials with which the steel may come in contact. Only when complete information is available on the physical and chemical properties of steels after certain heat treatments in the sections required can the most suitable type be selected for a given application.

TABLE III

S.A.E. STANDARD SPECIFICATIONS FOR STEELS*

Carbon Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus Max.	Sulphur Max.
1010	0.05–0.15	0.30–0.60	0.045	0.055
1015	0.10–0.20	0.30–0.60	0.045	0.055
X1015	0.10–0.20	0.70–1.00	0.045	0.055
1020	0.15–0.25	0.30–0.60	0.045	0.055
X1020	0.15–0.25	0.70–1.00	0.045	0.055
1025	0.20–0.30	0.30–0.60	0.045	0.055
X1025	0.20–0.30	0.70–1.00	0.045	0.055
1030	0.25–0.35	0.60–0.90	0.045	0.055
1035	0.30–0.40	0.60–0.90	0.045	0.055
1040	0.35–0.45	0.60–0.90	0.045	0.055
X1040	0.35–0.45	0.40–0.70	0.045	0.055
1045	0.40–0.50	0.60–0.90	0.045	0.055
X1045	0.40–0.50	0.40–0.70	0.045	0.055
1050	0.45–0.55	0.60–0.90	0.045	0.055
X1050	0.45–0.55	0.40–0.70	0.045	0.055
1055	0.50–0.60	0.60–0.90	0.040	0.055
X1055	0.50–0.60	0.90–1.20	0.040	0.055
1060	0.55–0.70	0.60–0.90	0.040	0.055
1065	0.60–0.75	0.60–0.90	0.040	0.055
X1065	0.60–0.75	0.90–1.20	0.040	0.055
1070	0.65–0.80	0.60–0.90	0.040	0.055
1075	0.70–0.85	0.60–0.90	0.040	0.055
1080	0.75–0.90	0.60–0.90	0.040	0.055
1085	0.80–0.95	0.60–0.90	0.040	0.055
1090	0.85–1.00	0.60–0.90	0.040	0.055
1095	0.90–1.05	0.25–0.50	0.040	0.055

Free Cutting Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus Range	Sulphur Range
1112	0.08–0.16	0.60–0.90	0.09–0.13	0.10–0.20
X1112	0.08–0.16	0.60–0.90	0.09–0.13	0.20–0.30
1115	0.10–0.20	0.70–1.00	0.045 max.	0.075–0.15
1120	0.15–0.25	0.60–0.90	0.045 max.	0.075–0.15
X1314	0.10–0.20	1.00–1.30	0.045 max.	0.075–0.15
X1315	0.10–0.20	1.30–1.60	0.045 max.	0.075–0.15
X1330	0.25–0.35	1.35–1.65	0.045 max.	0.075–0.15
X1335	0.30–0.40	1.35–1.65	0.045 max.	0.075–0.15
X1340	0.35–0.45	1.35–1.65	0.045 max.	0.075–0.15

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TABLE III—*Continued*

Manganese Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.
T1330	0.25-0.35	1.60-1.90	0.040	0.050
T1335	0.30-0.40	1.60-1.90	0.040	0.050
T1340	0.35-0.45	1.60-1.90	0.040	0.050
T1345	0.40-0.50	1.60-1.90	0.040	0.050
T1350	0.45-0.55	1.60-1.90	0.040	0.050

Nickel Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.	Nickel Range
2015	0.10-0.20	0.30-0.60	0.040	0.050	0.40-0.60
2115	0.10-0.20	0.30-0.60	0.040	0.050	1.25-1.75
2315	0.10-0.20	0.30-0.60	0.040	0.050	3.25-3.75
2320	0.15-0.25	0.30-0.60	0.040	0.050	3.25-3.75
2330	0.25-0.35	0.50-0.80	0.040	0.050	3.25-3.75
2335	0.30-0.40	0.50-0.80	0.040	0.050	3.25-3.75
2340	0.35-0.45	0.60-0.90	0.040	0.050	3.25-3.75
2345	0.40-0.50	0.60-0.90	0.040	0.050	3.25-3.75
2350	0.45-0.55	0.60-0.90	0.040	0.050	3.25-3.75
2515	0.10-0.20	0.30-0.60	0.040	0.050	4.75-5.25

Nickel Chromium Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.	Nickel Range	Chromium Range
3115	0.10-0.20	0.30-0.60	0.040	0.050	1.00-1.50	0.45-0.75
3120	0.15-0.25	0.30-0.60	0.040	0.050	1.00-1.50	0.45-0.75
3125	0.20-0.30	0.50-0.80	0.040	0.050	1.00-1.50	0.45-0.75
3130	0.25-0.35	0.50-0.80	0.040	0.050	1.00-1.50	0.45-0.75
3135	0.30-0.40	0.50-0.80	0.040	0.050	1.00-1.50	0.45-0.75
3140	0.35-0.45	0.60-0.90	0.040	0.050	1.00-1.50	0.45-0.75
X3140	0.35-0.45	0.60-0.90	0.040	0.050	1.00-1.50	0.60-0.90
3145	0.40-0.50	0.60-0.90	0.040	0.050	1.00-1.50	0.45-0.75
3150	0.45-0.55	0.60-0.90	0.040	0.050	1.00-1.50	0.45-0.75
3215	0.10-0.20	0.30-0.60	0.040	0.050	1.50-2.00	0.90-1.25
3220	0.15-0.25	0.30-0.60	0.040	0.050	1.50-2.00	0.90-1.25
3230	0.25-0.35	0.30-0.60	0.040	0.050	1.50-2.00	0.90-1.25
3240	0.35-0.45	0.30-0.60	0.040	0.050	1.50-2.00	0.90-1.25
3245	0.40-0.50	0.30-0.60	0.040	0.050	1.50-2.00	0.90-1.25
3250	0.45-0.55	0.30-0.60	0.040	0.050	1.50-2.00	0.90-1.25
3312	max. 0.17	0.30-0.60	0.040	0.050	3.25-3.75	1.25-1.75
3325	0.20-0.30	0.30-0.60	0.040	0.050	3.25-3.75	1.25-1.75
3335	0.30-0.40	0.30-0.60	0.040	0.050	3.25-3.75	1.25-1.75
3340	0.35-0.45	0.30-0.60	0.040	0.050	3.25-3.75	1.25-1.75
3415	0.10-0.20	0.30-0.60	0.040	0.050	2.75-3.25	0.60-0.95
3435	0.30-0.40	0.30-0.60	0.040	0.050	2.75-3.25	0.60-0.95
3450	0.45-0.55	0.30-0.60	0.040	0.050	2.75-3.25	0.60-0.95

TABLE III—*Continued*

Molybdenum Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.	Chromium Range	Nickel Range	Molybdenum Range
4130	0.25–0.35	0.50–0.80	0.040	0.050	0.50–0.80	....	0.15–0.25
X4130	0.25–0.35	0.40–0.60	0.040	0.050	0.80–1.10	....	0.15–0.25
4135	0.30–0.40	0.60–0.90	0.040	0.050	0.80–1.10	....	0.15–0.25
4140	0.35–0.45	0.60–0.90	0.040	0.050	0.80–1.10	....	0.15–0.25
4150	0.45–0.55	0.60–0.90	0.040	0.050	0.80–1.10	....	0.15–0.25
4320	0.15–0.25	0.40–0.70	0.040	0.050	0.30–0.60	1.65–2.00	0.20–0.30
4340	0.35–0.45	0.50–0.80	0.040	0.050	0.50–0.80	1.50–2.00	0.30–0.40
X4340	0.35–0.45	0.50–0.80	0.040	0.050	0.60–0.90	1.50–2.00	0.20–0.30
4615	0.10–0.20	0.40–0.70	0.040	0.050	....	1.65–2.00	0.20–0.30
4520	0.15–0.25	0.40–0.70	0.040	0.050	....	1.65–2.00	0.20–0.30
4640	0.35–0.45	0.50–0.80	0.040	0.050	....	1.65–2.00	0.20–0.30
4815	0.10–0.20	0.40–0.60	0.040	0.050	....	3.25–3.75	0.20–0.30
4820	0.15–0.25	0.40–0.60	0.040	0.050	....	3.25–3.75	0.20–0.30

Chromium Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.	Chromium Range
5120	0.15–0.25	0.30–0.60	0.040	0.050	0.60–0.90
5140	0.35–0.45	0.60–0.90	0.040	0.050	0.80–1.10
5150	0.45–0.55	0.60–0.90	0.040	0.050	0.80–1.10
52100	0.95–1.10	0.20–0.50	0.030	0.035	1.20–1.50

Chromium Vanadium Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.	Chromium Range	Vanadium	
						Min.	Desired
6115	0.10–0.20	0.30–0.60	0.040	0.050	0.80–1.10	0.15	0.18
6120	0.15–0.25	0.30–0.60	0.040	0.050	0.80–1.10	0.15	0.18
6125	0.20–0.30	0.60–0.90	0.040	0.050	0.80–1.10	0.15	0.18
6130	0.25–0.35	0.60–0.90	0.040	0.050	0.80–1.10	0.15	0.18
6135	0.30–0.40	0.60–0.90	0.040	0.050	0.80–1.10	0.15	0.18
6140	0.35–0.45	0.60–0.90	0.040	0.050	0.80–1.10	0.15	0.18
6145	0.40–0.50	0.60–0.90	0.040	0.050	0.80–1.10	0.15	0.18
6150	0.45–0.55	0.60–0.90	0.040	0.050	0.80–1.10	0.15	0.18
6195	0.90–1.05	0.20–0.45	0.030	0.035	0.80–1.10	0.15	0.18

Table III—*Continued*

Tungsten Steels

S.A.E. No.	Carbon Range	Manganese, Max.	Phosphorus, Max.	Sulphur, Max.	Chromium Range	Tungsten Range
71360	0.50–0.70	0.30	0.035	0.040	3.00–4.00	12.00–15.00
71660	0.50–0.70	0.30	0.035	0.040	3.00–4.00	15.00–18.00
7260	0.50–0.70	0.30	0.035	0.040	0.50–1.00	1.50– 2.00

Silicon Manganese Steels

S.A.E. No.	Carbon Range	Manganese Range	Phosphorus, Max.	Sulphur, Max.	Silicon Range
9255	0.50–0.60	0.60–0.90	0.040	0.050	1.80–2.20
9260	0.55–0.65	0.60–0.90	0.040	0.050	1.80–2.20

Corrosion and Heat Resisting Alloys

S.A.E. No.	Carbon, Max.	Manganese, Max.	Silicon, Max.	Phosphorus, Max.	Sulphur, Max.	Chromium Range	Nickel Range
30905	0.08	0.20–0.70	0.75	0.030	0.030	17.00–20.00	8.00–10.00
30915	0.09–0.20	0.20–0.70	0.75	0.030	0.030	17.00–20.00	8.00–10.00
51210	0.12	0.60	0.50	0.030	0.030	11.50–13.00	....
X51410	0.12	0.60	0.50	0.030	0.15–0.50	13.00–15.00	....
51335	0.25–0.40	0.60	0.50	0.030	0.030	12.00–14.00	....
51510	0.12	0.60	0.50	0.030	0.030	14.00–16.00	....
51710	0.12	0.60	0.50	0.030	0.030	16.00–18.00	....

Silicon range of all *S.A.E.* basic open hearth alloy steels except silicon manganese steels shall be 0.15–0.30. For electric and acid open hearth alloy steels except silicon manganese steels, the silicon content shall be 0.15 minimum.

S.A.E. Classification

The purchase specifications for steel which is to be forged or heat treated in the process of manufacture are usually based on chemical composition because the final physical properties will in large measure be determined by the treatment which the steel receives. The limits or ranges of composition are determined from the requirements of each application. The classification of steels as proposed by the *Society of Automotive Engineers* has been widely adopted by manufacturers and purchasers of steel. In the *S.A.E.* classification, the limits or ranges of the chemical elements are designated by numbers which can be used conveniently in specifications, in reports, and on shop drawings.

In arranging the numbers in the *S.A.E.* specifications, which are given in Table III, the first figure indicates the type to which the steel belongs: thus "1–" indicates a carbon steel, "2–" a nickel steel, and "3–" a nickel-chromium steel. In the numbers for alloy steels, the second figure indicates the approximate percentage of the predominant alloying element and the last two figures indicate the average carbon content in points or hundredths of 1 per cent. Thus "2340" indicates a nickel steel of approximately 3 per cent nickel (3.25 to 3.75), and 0.40 per cent carbon (0.35 to 0.45); and 71360 indicates a tungsten steel of about 13 per cent tungsten (12 to 15) and 0.60 per cent carbon (0.50 to 0.70). The prefix "X" is used in several instances to denote variations in the range of manganese, sulphur, or chromium. The prefix "T" is used with the high-manganese steels (1300 Series) to avoid confusion with steels of somewhat different manganese range that have been identified by the same numerals but without the prefix.

The basic numerals for the various types of *S.A.E.* steels are:

Carbon Steels	1–––
Plain Carbon	10––
Free Cutting (Screw Stock)	11––
Free Cutting, Manganese	X13––
High-Manganese	T13––
Nickel Steels	2–––
0.50 Per Cent Nickel	20––
1.50 Per Cent Nickel	21––
3.50 Per Cent Nickel	23––
5.00 Per Cent Nickel	25––
Nickel Chromium Steels	3–––
1.25% Nickel, 0.60% Chromium	31––
1.75% Nickel, 1.00% Chromium	32––
3.50% Nickel, 1.50% Chromium	33––
3.00% Nickel, 0.80% Chromium	34––
Corrosion and Heat Resisting Steels	30–––
Molybdenum Steels	4–––
Chromium	41––
Chromium Nickel	43––
Nickel	46–– and 48––
Chromium Steels	5–––
Low Chromium	51––
Medium Chromium	52–––
Corrosion and Heat Resisting	51–––
Chromium Vanadium Steels	6–––
Tungsten Steels	7––– and 7––––
Silicon Manganese Steels	9–––

CLASSES BASED ON THE GRAIN SIZE OF STEEL

The chemical composition alone is not sufficient to explain the variations in the properties of heat-treated steels. Another factor, which is influenced by the steel-making practice, is the grain size of the steel. A standard procedure has been proposed by the *American Society for Testing Materials* for the classification of steel on the basis of grain size. Specimens of steel are carburized at 1700 degrees F. for 8 hours and are cooled slowly in the furnace. An examination is then made of the carburized zone on the specimens at a magnification of 100 diameters. The size of the grains in the high-carbon steel is compared with a standard chart, Fig. 38 in Chapter VI, listing a series of grain sizes from No. 1 coarse to No. 8 fine. As a rule, steel is specified in a range of grain sizes; the first four sizes in the chart are considered as "coarse-grained" steel and the last four sizes as "fine-grained" steel. The choice of either coarse- or fine-grained steel is dependent upon the requirements of the parts to be made from the steel. The relation of grain size to heat-treating practice and the resulting properties is discussed in Chapter VI.

CLASSES BASED ON THE USES OF STEEL

Another method for classifying commercial steels is according to their applications. The two main groups into which all steels may be placed are designated as **constructional steels** and **tool steels.** These terms are used frequently when referring to the types of steels for different kinds of service.

Constructional Steels

In general, the requirements of constructional steels are strength, ductility, and ease of machining. The steels in this group are employed in the construction of buildings, bridges, ships, and automobiles, as well as for equipment and machinery of all kinds. Both carbon steels and alloy steels are used for these purposes. The compositions and properties of alloy constructional steels are discussed in Chapter X.

Low-Carbon Steels—A special type of metal known as **ingot iron** having a carbon content between 0.01 and 0.05 per cent is produced in the basic open-hearth furnace. This product usually contains less than 0.16 per cent of all elements other than iron. Because of its purity, ingot iron is fairly resistant to corrosion. It is supplied in the form of sheets, plates, and wire.

A large quantity of constructional steel is made with a carbon content between 0.05 and 0.30 per cent. The steel used extensively for welded structures is within this classification. Most of the sheet steel and tin plate are manufactured from basic open-hearth or Bessemer steel having a carbon content of 0.05 to 0.12 per cent. Welded pipe and most seamless tubing are made of steel with the carbon content below 0.20 per cent. Channels, angles, I-beams, and other structural sections for buildings and bridges are usually made of steel containing less than 0.30 per cent carbon. Drop forgings are often made from steel in this class. As a rule, the low-carbon steels are used without being heat treated, except for parts which are case hardened.

Medium-Carbon Steels—Those steels containing 0.30 to 0.60 per cent carbon are employed extensively for machine parts requiring a combination of high strength and favorable ductility. Steels within this range of carbon are particularly suited to medium and heavy forgings such as are used for crankshafts, connecting rods, axles, driveshafts, gears, crane hooks, and guns. Whereas the medium-carbon steels are sometimes used in the hot-rolled or forged condition, superior properties are obtained after suitable heat treatments.

Tool Steels

The steels belonging to this group are used for cutting and forming metals or other materials. The chief requirements of tool steel are great hardness and resistance to wear after heat treatment. In this group are the carbon steels with the carbon content greater than 0.60 per cent, and the special alloy steels. Some uses of carbon tool steels with their ranges of carbon content are included in Table IV. Several types

TABLE IV

CARBON CONTENT OF STEELS FOR DIFFERENT USES

Carbon Range, Per Cent	Uses of Carbon Steel
0.05–0.15	Pipe, chain, rivets, screws, nails, stampings
0.15–0.30	Structural sections, plates, bars, carburized parts
0.30–0.40	Axles, connecting rods, shafting
0.40–0.50	Crankshafts, gears, crane hooks
0.50–0.60	Scraper blades
0.60–0.70	Dies for drop hammers, set screws, locomotive tires
0.70–0.80	Anvil faces, band saws, smithing hammers, rails
0.80–0.90	Punches, rock drills, cold chisels, rivet sets
0.90–1.00	Springs, axes, knives, shear blades
1.00–1.10	Milling cutters, flat drills, taps
1.10–1.20	Lathe tools, twist drills, wood chisels
1.20–1.30	Files, reamers
1.30–1.40	Wire-drawing dies, razors, brass-turning tools
1.40–1.50	Saws for cutting steel

of alloy tool steel are described in Chapter X. Tool steels are generally supplied in round, square, and rectangular bars, varying by $\frac{1}{16}$ inch in sizes from $\frac{3}{16}$ to $1\frac{1}{2}$ inches, and by $\frac{1}{8}$ inch in sizes to 3 inches. Some tool steels are also available in hexagon and octagon shapes. Manufacturers of tool steels often supply special steels in the form of heat-treated tool bits or blanks of specified sizes. Another product in this group is **drill rod,** which is usually a high-carbon tool steel or high-speed steel furnished in round bars with polished surfaces, in accurate sizes up to $1\frac{1}{2}$ inches in diameter.

A.S.T.M. Specifications

The standard specifications of the *American Society for Testing Materials* are based on the uses of steel and usually give the minimum physical properties, together with the limiting amounts of phosphorus and/or sulphur in the steel. As an illustration, structural steel for buildings (*A.S.T.M.* Designation: A9–36) has the following requirements as to tensile properties: "Tensile strength 60,000 to 72,000 lb. per sq. in.; yield point one-half of the tensile strength, but in no case less than 33,000 lb. per sq. in.; and percentage elongation in 2 inches of 22 per cent." In this specification, the maximum phosphorus for Bessemer steel is given at 0.10 per cent, and for open-hearth or electric-furnace steel at 0.06 per cent.

The standard specifications for mild steel plates for general plate construction (*A.S.T.M.* Designation A10–34) give the following requirements as to tensile properties: "Tensile strength 55,000 to 65,000 lb. per sq. in.; yield point one-half of the tensile strength, but in no case less than 30,000 lb. per sq. in.; and percentage elongation in 2 inches of 24 per cent." In this specification, the maximum phosphorus for steel made with acid practice is 0.06 per cent and with basic practice is 0.04 per cent. The maximum sulphur is specified at 0.05 per cent. Other specifications in the book of *A.S.T.M. Standards* include steel for bridges, steel for locomotives and cars, steel for ships, steel for boilers, steel for welded and seamless steel pipe, steel for rails, and steel for springs.

CLASSES BASED ON THE CONDITION AND FORM OF STEEL

The two conditions in which steel is used are designated as cast steel, and wrought or worked steel. Metal which is cast directly from the steel-making furnaces into the shapes in which it is finally used is known as **cast steel.** Metal which is first cast into an ingot and later worked to the desired shapes is known as **rolled steel** or **forged steel.** The largest proportion of the total production of steel is mechanically worked before being applied to industrial uses.

Semi-Finished Steel

In the preliminary stages of working steel, the metal in an ingot is gradually reduced to pieces of smaller size known as blooms, billets, and slabs. **Blooms** are approximately square and have a cross-sectional area of over 36 square inches. **Billets** have sections of 4 to 36 square inches in area. **Slabs** are rectangular pieces in which the width is equal to at least twice the thickness. These semi-finished products from the roughing mills require additional working to convert them into finished products such as bars, plates, sheets, strips, rails, structural sections, and forgings. The rough shapes are either formed directly into finished products or are allowed to cool and then shipped to rolling mills or forging shops for further processing. Refer to Table VIII in Chapter VII.

Finished Steel

Steel is manufactured in a number of different forms which are rolled to the required sizes for industrial uses. A view of the stock in one division of a steel warehouse is shown in Fig. 25. In addition to the standard structural sections such as angles, channels, and I-beams,

Courtesy of Joseph T. Ryerson & Son Company

FIG. 25—VIEW IN STEEL WAREHOUSE

steel is made into flat hot-rolled stock such as strips, sheets, plates, and bars. **Strips** are less than $\frac{1}{4}$ inch in thickness and less than 24 inches in width. **Sheets** are less than $\frac{1}{4}$ inch in thickness and 24 inches and over in width. **Plates*** are $\frac{1}{4}$ inch and over in thickness and over 6 inches in width. **Bars** are $\frac{1}{4}$ inch and over in thickness and 6 inches and less in width.

Large quantities of steel are produced in solid round sections such as bars, rods, and wire. Wire rod is the finished product of the hot-rolling mill, but constitutes the raw material for the wire mill. It is made in continuous lengths as long as commercial operation permits. **Wire rod** ranges from 0.734 inch down to 0.207 inch in diameter. Sizes larger are classified as **bars,** and smaller sizes as **wire.** Many other regular shapes such as hexagon and octagon, as well as special shapes, are produced by hot rolling.

Another group of finished steel products includes hollow forms such as pipe and tubing which are used for conveying gases, liquids, and solids, as well as for a large number of mechanical and structural purposes. The processes used in making welded pipe and seamless tubing are described in Chapter VII. Tubular products are made of carbon and alloy steels in many different compositions for specific applications. However, most welded pipe and seamless tubing are produced from carbon steel containing less than 0.20 per cent carbon. Pipe sizes are designated by the nominal inside diameter in inches. Standard dimensions for inside diameters and wall thicknesses have been adopted by manufacturers and users of steel pipe. On the other hand, the size of seamless tubing is usually based on its outside diameter and wall thickness. Welded pipe is made in sizes up to 26 inches and seamless tubing as large as 14 inches in diameter. In addition to the more common circular sections, steel tubing is produced in square, hexagon, and many other special shapes.

The finishing operations on steel leave the metal in either of two conditions designated as **hot-finished** and **cold-finished** steel. Large tonnages of hot-rolled steel bars are made into bolts, tie rods, pins, shafts, and other parts of machines. The largest size of rounds which are hot rolled is about 8 inches in diameter. Shafts of larger size are forged from blooms or directly from ingots.

After steel has been worked at high temperatures, a coating of iron oxide or mill scale remains on the metal. This condition of the surface of hot-finished steel is not satisfactory for some applications. When the mill scale is removed from hot-rolled steel and the metal is subjected to cold-rolling or cold-drawing operations, bright, smooth surfaces are obtained. Furthermore, accurate dimensions of the commercial forms of steel can be secured as a result of cold working.

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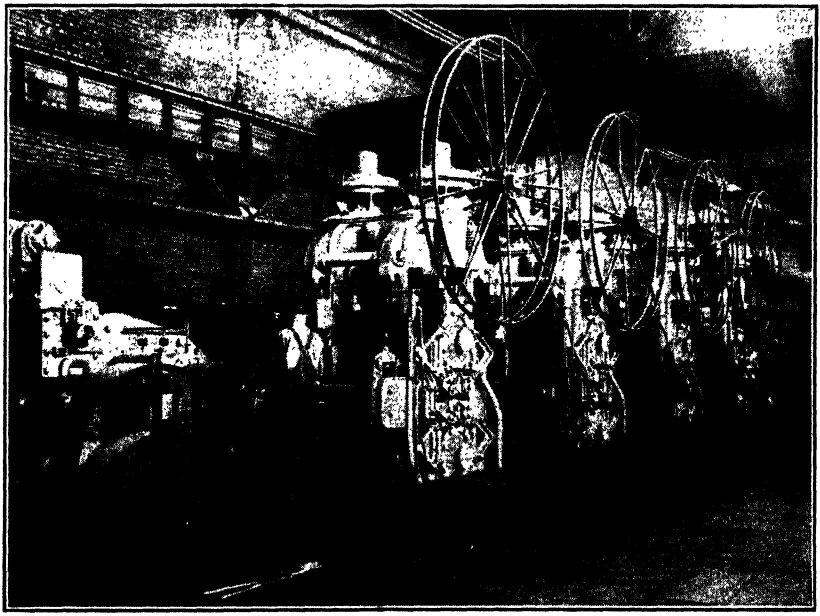
* Flat-rolled stock over 48 inches in width and over $\frac{3}{16}$ inch in thickness is designated as plates.

Cold-rolled steel in flat stock such as strips and sheets is produced in several degrees of hardness, designated as dead soft, skin-rolled, quarter hard, half hard, and hard. The variations in physical properties are dependent on the amount of cold working to which the steel is subjected after it has been annealed. Dead-soft stock is used for parts which are formed to shape by deep drawing or other severe cold-working operations. Skin-rolled material is obtained by a light cold rolling after annealing; this steel is used in making moldings, stampings, and other products. Quarter-hard stock can be bent down upon itself across the grain flow and to some extent with the grain flow. Half-hard material can be bent at right angles across the grain flow. Hard sheets and strips are used chiefly for flat articles.



Courtesy of E. W. Bliss Company

FIG. 26—FOUR-HIGH TANDEM MILL FOR COLD-ROLLED STRIP STEEL

Smooth surfaces on round bars of steel which are too large to be cold drawn satisfactorily (sizes larger than $2\frac{15}{16}$ inches in diameter) are obtained by turning and polishing, or turning and grinding bars of hot-rolled steel. Cold-finished steel shafting is used extensively for transmitting mechanical power. Bearings, pulleys, and collars are fitted to the shafting, and close tolerances are required to permit easy assemblage. The standard tolerances for cold-finished bars are as follows:

> Sizes up to and including 1 inch round, over 0.000 inch and under 0.002 inch.
> From $1\frac{1}{16}$ inches round to 2 inches round inclusive, over 0.000 inch and under 0.003 inch.
> From $2\frac{1}{16}$ inches round to 4 inches round inclusive, over 0.000 inch and under 0.004 inch.
> From $4\frac{1}{16}$ inches round to 6 inches round inclusive, over 0.000 inch and under 0.005 inch.

Rolling mills for the manufacture of cold-rolled strip steel are shown in Fig. 26.

Grades of Bar Steel

The quality of steel is dependent to a large extent upon the steelmaking and rolling-mill practice. Three classes established by manufacturers of hot-rolled carbon steel bars are designated as commercial quality, forging quality, and special quality. **Commercial quality** implies that the steel is free from defects which would be injurious for ordinary purposes. **Forging quality** requires special precautions in the manufacture of the steel to produce material suitable for forging, heat treating, or similar purposes in which uniformity of composition and freedom from injurious defects are essential. Steel of **special quality** is obtained by special restrictions such as the amount of discard during rolling, close control of chemical analysis, and a guarantee of the properties of the steel after it is heat treated.

REVIEW QUESTIONS

1. Account for the quality of steel produced by the basic open-hearth process.
2. What types of steels are usually made by the Bessemer process?
3. Explain the methods of classifying carbon steels.
4. Explain the basis for the *S.A.E.* classification of steels.
5. Discuss the classification of steels based on grain size.
6. What are the chief requirements of each of the two classes of steel determined by their uses?
7. What is the correct designation of steel supplied in lengths of 14 feet and having a cross section of 4 inches by $\frac{3}{8}$ inch?
8. What requirements are given in the *A.S.T.M.* specifications for structural steel for buildings?
9. Define hot-finished billets and cold-finished sheets.
10. What grades of quality can be obtained in bar steel?

CHAPTER V

THE PHYSICAL CONSTITUTION OF STEEL

CRITICAL TEMPERATURES OF STEEL—SOLID PHASES IN STEEL—**Ferrite—Cementite—Austenite**—PRIMARY CONSTITUENTS—**Martensite—Primary Troostite—Pearlite**—SECONDARY CONSTITUENTS—**Secondary Troostite—Sorbite—Spheroidized Cementite**—REVIEW OF PHYSICAL CONSTITUENTS—CONSTITUENTS IN SLOWLY COOLED CARBON STEEL

Carbon steel contains in addition to iron varying proportions of carbon, manganese, silicon, sulphur, and phosphorus. The effects of these elements on the properties of carbon steel are described in Chapter III. Additional alloying elements such as nickel, chromium, molybdenum, tungsten, and vanadium are found in alloy steels. All the chemical elements are present in combinations which make up the physical structure of steel. The physical properties are dependent directly upon the proportions of the different physical constituents which are present. In turn, the physical constituents are determined by the chemical composition of the steel and the heat treatment to which it is subjected.

The names of the chief microscopic constituents which may be present in steel are ferrite, cementite, austenite, pearlite, primary troostite, martensite, secondary troostite, and sorbite. These constituents are identified with the aid of a microscope after specimens have been carefully polished and then etched with dilute acids or other corrosive solutions which attack in varying degree the different constituents in the metal. This method of inspection also indicates the size and shape of the grains as well as the presence of non metallic inclusions such as manganese sulphide in the steel.

CRITICAL TEMPERATURES OF STEEL

When a piece of steel is heated uniformly to high temperatures in the solid state, certain retardations occur in the rate at which the temperature of the steel increases. Likewise, when the steel is cooled from these high temperatures, other retardations occur in the rate at which the temperature of the steel decreases. When the changes in the temperature of the steel, which take place during the heating and cooling cycle, are noted at regular intervals of time, and the data are plotted, curves similar to those in Fig. 27 will be obtained. The retardations in the rising temperatures occurring while the steel is being heated are indicated by points 1 and 2, and the retardations during cooling are at points 3 and 4. The temperatures at which these retardations occur are known as **critical points** or **critical temperatures.** The range of temperatures between points 1 and 2 is described as the **thermal critical range on heating,** and the temperature range between points 3 and 4 is the **thermal critical range on cooling** for steel of a specific composition.

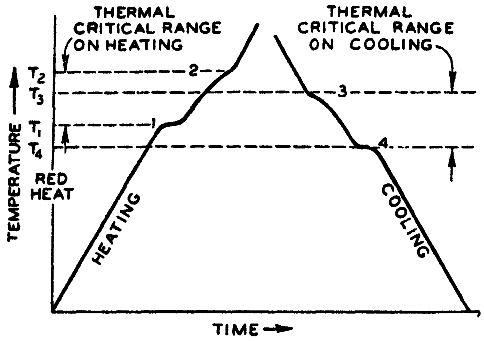


FIG. 27—HEATING AND COOLING CURVES FOR LOW-CARBON STEEL

When steel is heated to temperatures above the critical range, the absorption of heat by the steel while it passes through the critical range is an indication of a transformation taking place in the crystal structure of the steel. Also, the evolution of heat when the steel is cooled through the critical range is an indication of the transformation in crystal structure back to the original structure. The critical temperatures found on cooling are somewhat lower than the corresponding points obtained on heating. A carbon steel containing about 0.83 per cent carbon has only one critical point on heating, because the transformation in the structure takes place at one temperature.

When the critical temperatures on heating for carbon steels with different carbon contents are determined experimentally and are plotted against carbon contents, the **thermal critical range diagram** as given in Fig. 28 will be obtained. On this diagram, *C–E–D* locates the upper critical temperatures on heating, and *A–E–B* locates the lower critical temperatures on heating. The areas between these lines locate the critical ranges for all carbon steels. The critical range diagram serves to establish the temperatures used for mechanical working and for heat treating steel. Reference will be made to this diagram in the following discussion on the physical constitution of steel.

SOLID PHASES IN STEEL

The fundamental physical constituents in steel may be considered as different solid phases that are present in its structure. These phases

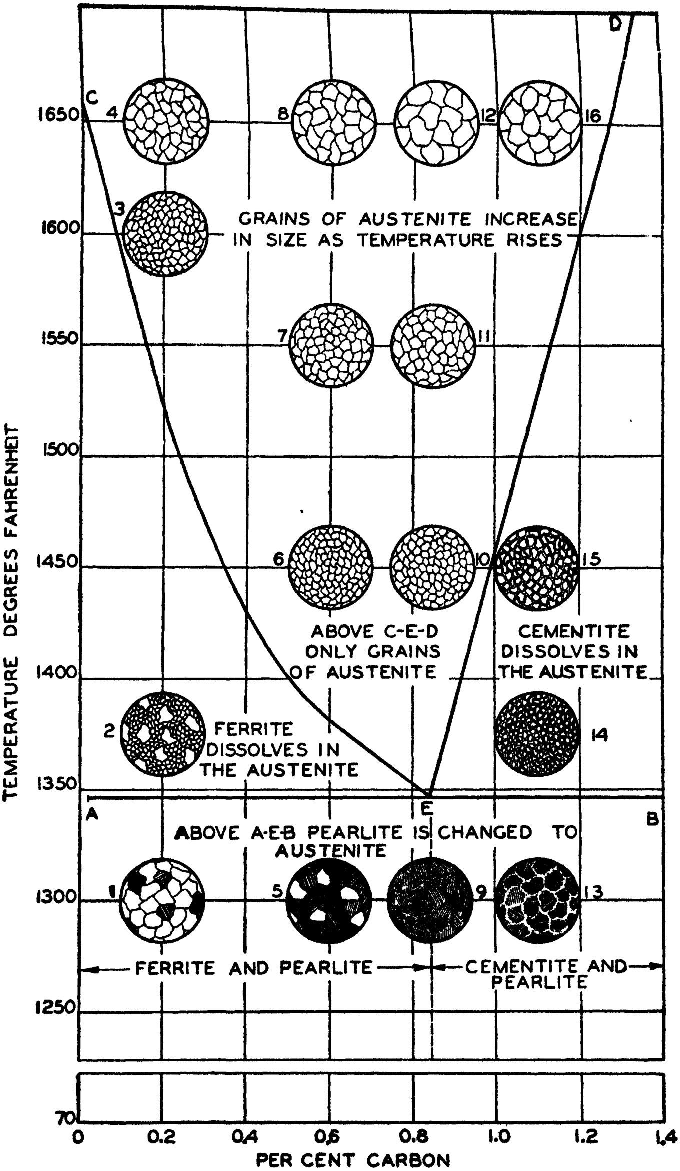

TEMPERATURE DEGREES FAHRENHEIT
1650
1600
1550
1500
1450
1400
1350
1300
1250
70
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
PER CENT CARBON
C
D
A
E
B
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
GRAINS OF AUSTENITE INCREASE IN SIZE AS TEMPERATURE RISES
ABOVE C-E-D ONLY GRAINS OF AUSTENITE
CEMENTITE DISSOLVES IN THE AUSTENITE
FERRITE DISSOLVES IN THE AUSTENITE
ABOVE A-E-B PEARLITE IS CHANGED TO AUSTENITE
FERRITE AND PEARLITE
CEMENTITE AND PEARLITE

Fig. 28—Critical Ranges on Heating for Carbon Steel

are distinct homogeneous parts of the physical structure of which the other more complex constituents are composed. The phases present in any specimen of steel depend on the chemical composition of the steel and on its temperature. The range of temperatures and the range of carbon contents at which each phase occurs are shown in Fig. 28. These phases are designated as ferrite, cementite, and austenite.

Ferrite

Ferrite is the phase which is composed of iron together with small amounts of other elements in solid solution. At room temperature only about 0.008 per cent carbon is soluble in ferrite at equilibrium. Grains of free ferrite are found in all carbon steels containing less than 0.83 per cent carbon after these steels have been cooled slowly from temperatures above or within the critical range. Ferrite also occurs as one of the components in other more complex constituents at temperatures below the critical range. As ferrite is attacked readily by etching solutions, individual grains of free ferrite appear as slightly roughened white patches (Fig. 29) at high magnifications.

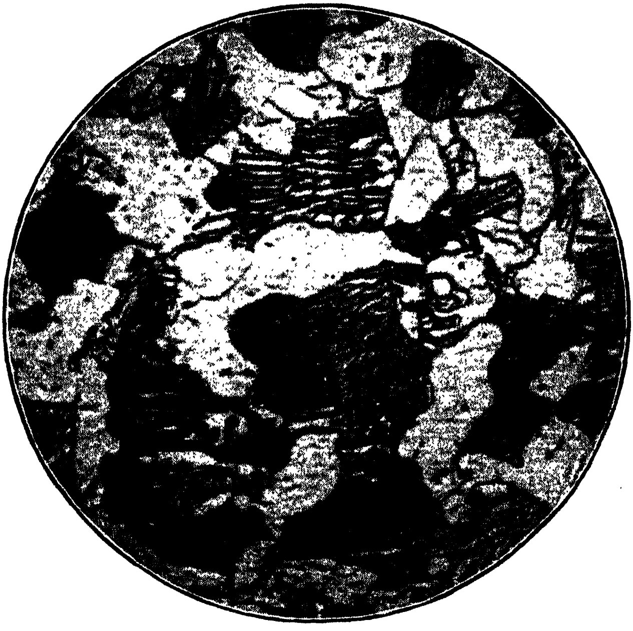


FIG. 29—FERRITE AND PEARLITE, × 1000

Light constituent is ferrite and laminated constituent is pearlite. Specimen of carbon steel containing 0.55 per cent carbon, cooled slowly from 1475 degrees F.

Ferrite is relatively soft and ductile. It has a Brinell hardness of about 90 and is machinable. The tensile strength of ferrite is about 40,000 lb. per sq. in. with an elongation of about 40 per cent. Ferrite is strongly magnetic.

Cementite

Cementite is a chemical compound of iron and carbon having the formula Fe_3C and containing 93.33 per cent iron and 6.67 per cent carbon by weight. Other elements such as manganese in carbon steels, and chromium, molybdenum, vanadium, and manganese in alloy steels, form carbides which occur with Fe_3C in cementite. Free cementite is the white phase at the grain boundaries of the pearlite in Fig. 30. It is also identified as round particles in the structure shown in Fig. 36. Free cementite is found in all steels containing over 0.83 per cent carbon after they have been cooled slowly from within or just above the critical range. Cementite also occurs as one of the components in other more complex constituents at temperatures below the critical range.

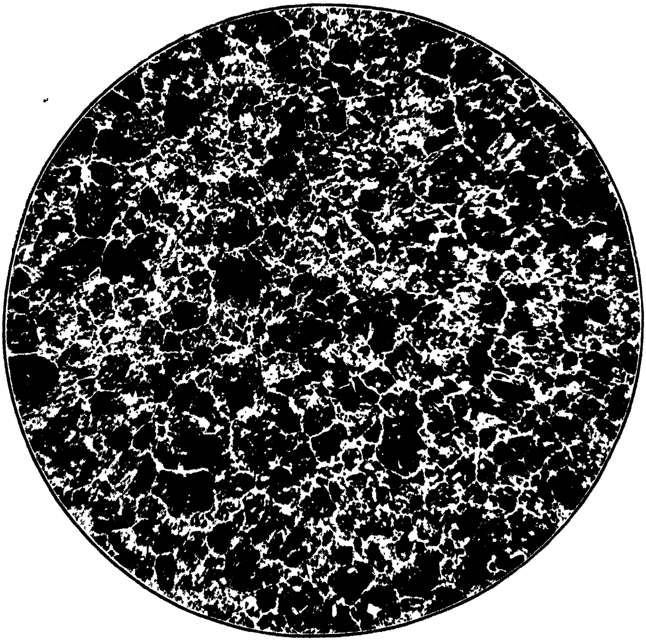


FIG. 30—PEARLITE AND CEMENTITE, × 100

Dark constituent is pearlite, and light constituent surrounding grains of pearlite is free cementite. Specimen of carbon steel containing 1.25 per cent carbon, cooled in the furnace from 1675 degrees F.

As the Brinell hardness of cementite is about 650, it is one of the hardest constituents in steel, and has practically no ductility. Cementite is magnetic.

Austenite

Austenite is a solid solution* of carbon and other elements in iron. It is produced in carbon steels at temperatures within and above the critical range. As much as 1.7 per cent carbon may dissolve in austenite at 2065 degrees F. Steels are heated to the austenitic condition in certain heat treatments and also in preparation for forging. Austenite is non-magnetic and can be detected because of this property.

PRIMARY CONSTITUENTS

When carbon steel is cooled from temperatures above the critical range, the austenite may transform into several different constituents, depending on the rate at which it is cooled. Rapid cooling produces martensite having a needle-like appearance under the microscope. On the other hand, very slow cooling produces pearlite with a lamellar structure, and an intermediate rate of cooling produces primary troostite.

Martensite

Martensite is the hard constituent obtained when carbon steel is cooled rapidly from temperatures within or above the critical range. The lower the carbon content of the steel, the more rapid must be the cooling rate to obtain martensite. The maximum hardness of steels quenched in water from their hardening temperatures varies with the carbon content as shown in Fig. 76 in Chapter VIII.

Martensite is composed of needle-like crystals in angular arrangement as shown in Fig. 31. This structure is distinctly different from the lamellar structure that appears in the more slowly cooled steels. If the steel is not cooled fast enough to produce martensite completely, some primary troostite may be present with the martensite (see Fig. 32).

Quenched steel in the martensitic condition has greater strength and hardness than in any other condition. The ductility of martensite compared with other constituents is relatively low. Martensite is magnetic.

Primary Troostite

Primary troostite is the constituent formed when carbon steel in the austenitic condition is cooled at a slightly slower rate than is necessary to obtain all martensite, but at a faster rate than is required to produce pearlite. As this rate of cooling is not readily attained, primary troostite is usually accompanied by one of the other constituents.

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* A condition similar to a liquid solution in which the constituents are completely dissolved in each other in the solid state.

At a magnification of 1,000 diameters, primary troostite appears as dark rounded areas or nodules when occurring with martensite as shown in Fig. 32. At very high magnifications, however, this dark constituent appears to be composed of layers of ferrite and cementite much the same as the structure of pearlite. These layers are thinner than those in pearlite and are not as uniform. The carbon content of primary troosite may vary considerably from 0.83 per cent and in this respect primary troostite differs from pearlite.

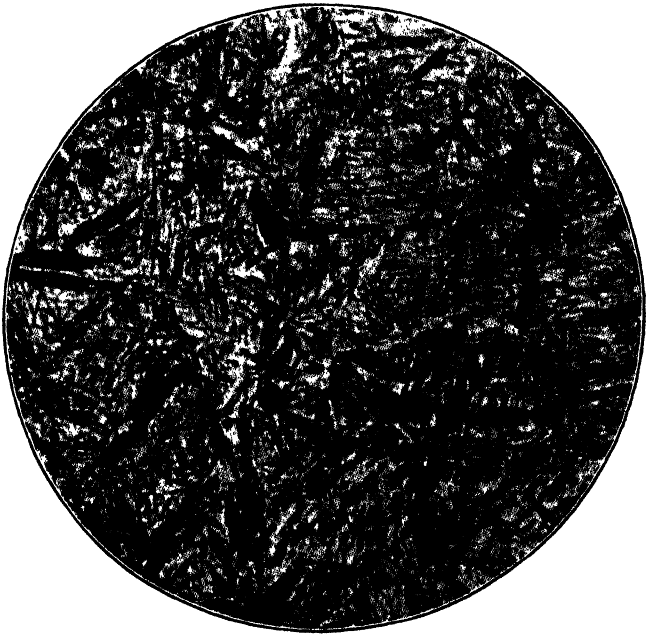


FIG. 31—MARTENSITE, × 1000

Needle-like crystals in angular arrangement. Specimen of carbon steel containing 0.45 per cent carbon, quenched in water from 1500 degrees F. Micrograph taken at the surface of the quenched specimen.

The strength and hardness of steel composed largely of primary troostite are greater than the strength and hardness of the same steel in the pearlitic condition. The ductility and machinability are less than for the pearlitic steel.

Pearlite

Pearlite is composed of alternate layers of the two phases, ferrite and cementite, as shown in Fig. 33. The carbon content of pearlite in carbon steels is approximately 0.83 per cent. When a carbon steel containing 0.83 per cent carbon is cooled slowly from temperatures above 1350 degrees F., it is composed entirely of grains of pearlite. Carbon steel of this approximate composition is known as **eutectoid steel.** All other carbon steels, however, contain some pearlite after they have cooled slowly from temperatures within or above the critical range. Grains of free ferrite occur with the pearlite in slowly cooled steels containing less than 0.83 per cent carbon designated as **hypoeutectoid steels** (see Fig. 34). In steels having more than 0.83 per cent carbon, known as **hypereutectoid steels,** the grains of pearlite are surrounded by a network of free cementite as shown in Fig. 30. In each case, pearlite is the last constituent to form from the austenite as the steel is cooled through the thermal critical range. The transformation from austenite to pearl-

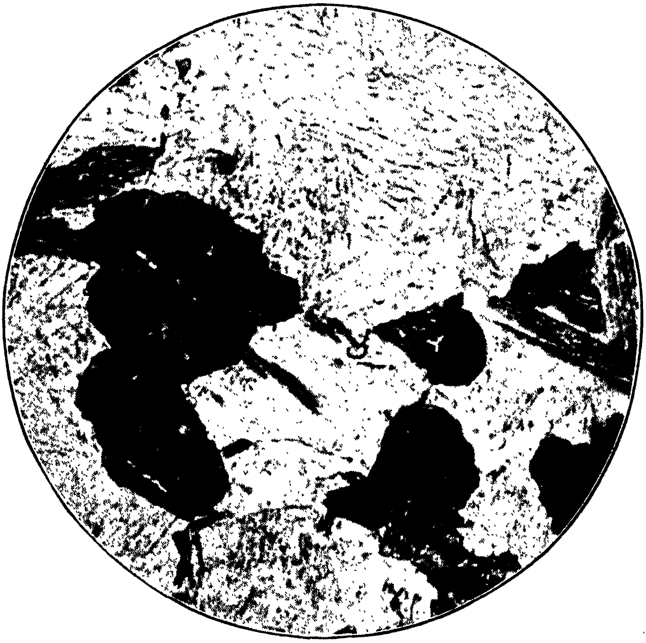


FIG. 32—PRIMARY TROOSTITE AND MARTENSITE, × 1000

Dark area with rounded outline is primary troostite. Light constituent is martensite. Specimen of carbon steel containing 0.55 per cent carbon, quenched in water from 1500 degrees F. Micrograph taken near the surface of the quenched specimen.

ite occurs only when the austenite has reached the eutectoid composition and when it has cooled to the lower critical temperature on cooling (about 1300 degrees F.).

When an etched specimen of steel containing pearlite is viewed under the microscope at low magnification (100 diameters), this constituent has a dark appearance as shown in Fig. 34, whereas, at a high magnification (1,000 diameters), the pearlite appears to have a laminated structure as shown in Fig. 29. The difference in the solubility of the ferrite and cementite layers in the grains of pearlite, when the specimen is etched, causes the characteristic appearance of this constituent at high magnification.

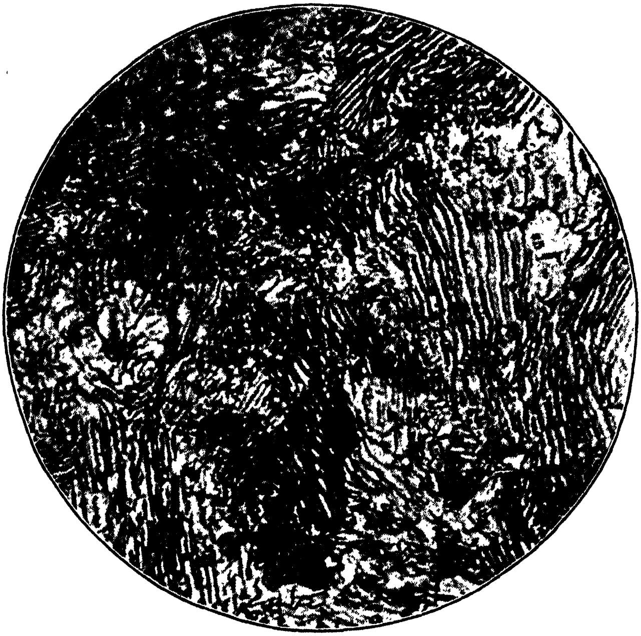


FIG. 33—PEARLITE, × 1000

Mixture of ferrite and cementite in layers. Light portion is ferrite and dark portion is cementite. Specimen of carbon steel containing 0.85 per cent carbon, cooled slowly from 1450 degrees F.

Steel composed entirely of pearlite has a tensile strength between 125,000 and 150,000 lb. per sq. in. with an elongation of about 10 per cent and a reduction of area of approximately 15 per cent. The Brinell hardness of pearlite ranges from 250 to 300, increasing in hardness as it becomes finer in structure. The pearlite constituent in steels is machinable.

SECONDARY CONSTITUENTS

Hardened steel (martensitic) is reheated to temperatures below the critical range to relieve the stresses which result from quenching, and to increase the ductility of the steel. This toughening treatment is known as **tempering** or **drawing.** The ductility of the hardened steel is increased as the tempering temperatures are raised. At the same time, the strength and the hardness of the quenched steel are proportionately decreased by tempering.

During the tempering treatment, the martensite formed as a result of quenching decomposes, and sub-microscopic particles of cementite are gradually formed. These particles of cementite coalesce to a size that can be seen at a magnification of 1,000 diameters only when the hardened steel is tempered at about 1000 degrees F. and above. The temperatures at which the secondary constituents are formed from martensite on tempering represent arbitrary divisions of the gradual coalescence of particles of cementite.

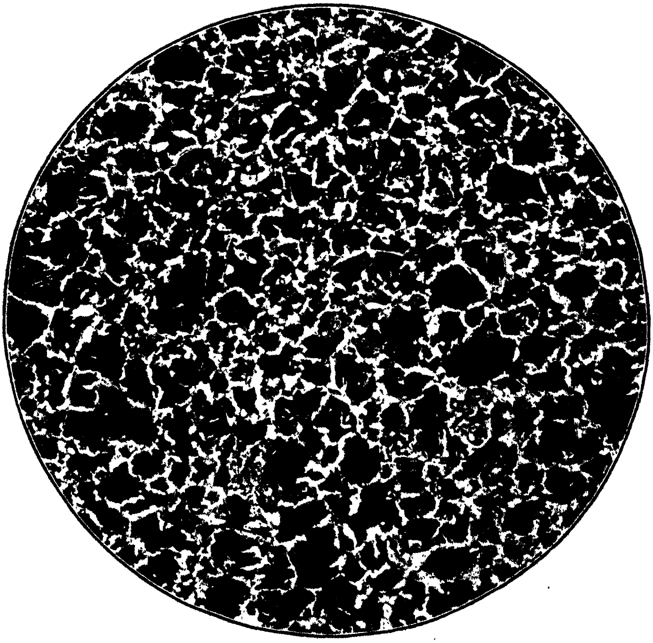


FIG. 34—PEARLITE AND FERRITE, × 100

Dark constituent is pearlite and light constituent is ferrite. Specimen of carbon steel containing 0.55 per cent carbon, cooled slowly from 1475 degrees F.

Secondary Troosite

When hardened carbon steel is tempered at temperatures between 400 and 750 degrees F., the structure changes gradually from martensite to a constituent known as secondary troostite, which has a dark appearance after etching. The strength and hardness of secondary troostite are lower than the strength and hardness of martensite in the same steel. The ductility, however, is increased by this tempering treatment. Steels which are composed of secondary troostite are difficult to machine.

Sorbite

A sorbitic structure (Fig. 35) is obtained when quenched carbon steel is tempered at temperatures between 750 and 1250 degrees F. Sorbite is not as strong nor as hard as secondary troostite in the same steel, but it has greater strength and hardness than pearlite. The desired strength and ductility of constructional steels are often obtained by heat treatments which develop a sorbitic structure. See Table IX in Chapter VIII. Steels in this condition can be machined, but not as readily as in the annealed state.

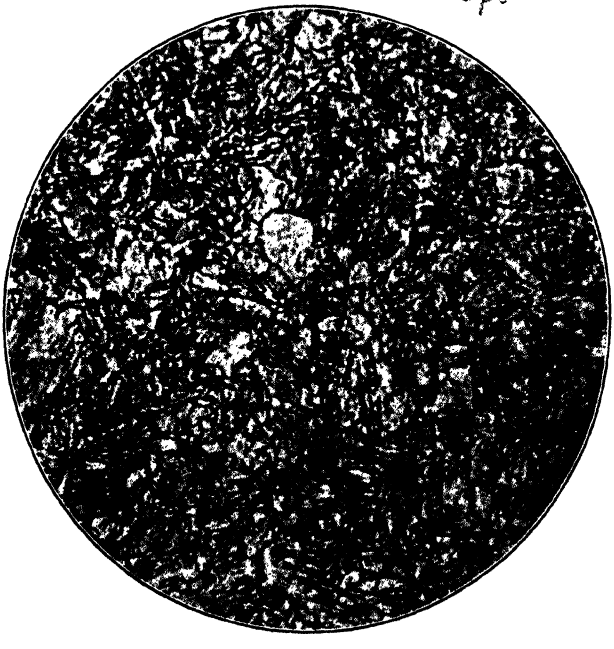


FIG. 35—SORBITE, × 1000

Mixture of small particles of cementite distributed in ferrite. Specimen of carbon steel containing 0.45 per cent carbon, quenched in water from 1500 degrees F. and tempered at 1100 degrees F.

Spheroidized Cementite

When hardened steel is heated at temperatures of 1250 to 1350 degrees F., the particles of cementite coalesce to a size that can be easily seen under the microscope. See Fig. 36. The particles of cementite are spherical in shape and are known as spheroidized cementite. The matrix of this structure is composed of ferrite.

Spheroidized cementite may also be produced from pearlite or primary troostite by prolonged heating within the temperature range of 1250 to 1350 degrees F. The cementite, originally in the laminated structures, coalesces to form spherical particles. Thus the same structure can be produced in different ways.

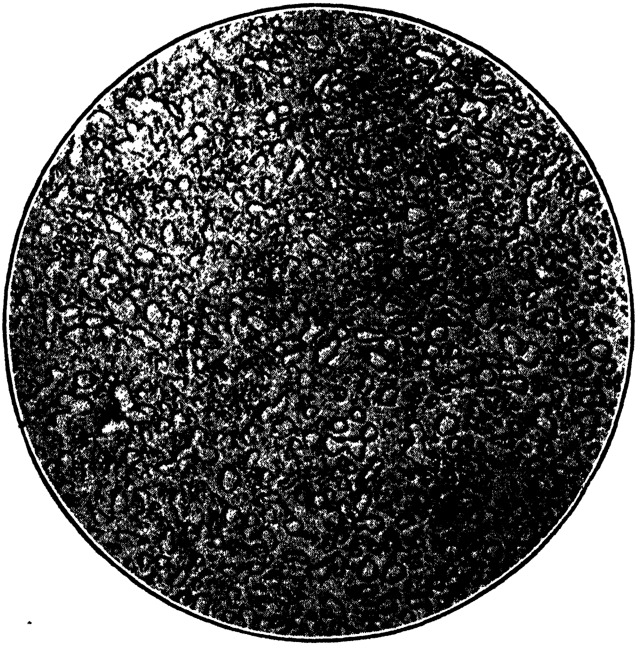


FIG. 36—SPHEROIDIZED STRUCTURE, × 750

Rounded areas of spheroidized cementite in matrix of ferrite. Specimen of carbon steel containing 1.20 per cent carbon heated for four hours at 1300 degrees F. after hardening.

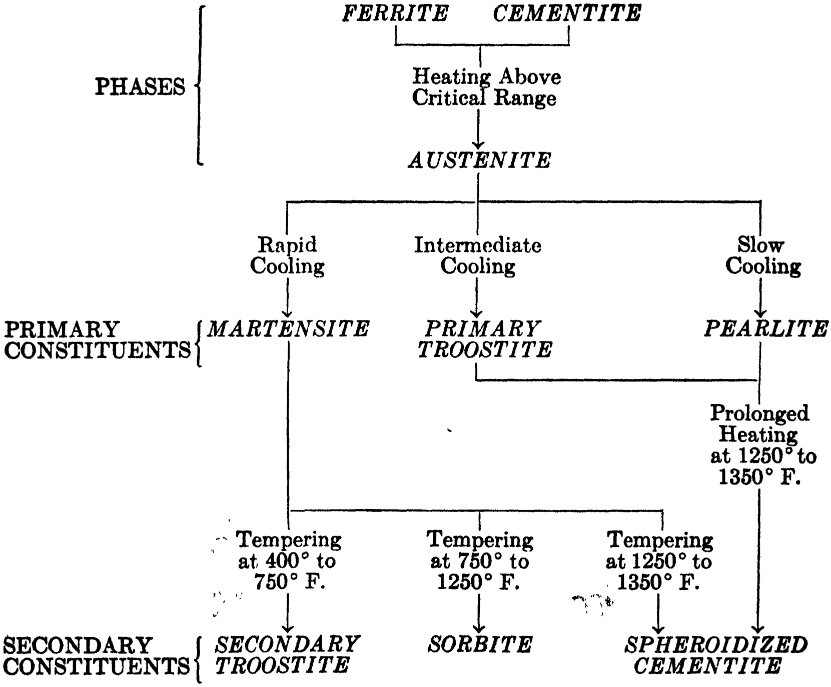
In the spheroidized condition, all steels have minimum hardness and strength, and maximum ductility. High-carbon steels are most readily machined when in this condition and must be heat treated again after machining to obtain the required final properties.

REVIEW OF PHYSICAL CONSTITUENTS

Ferrite, cementite, and austenite are the three principal phases that occur in steel. See Table V. The primary and secondary constituents are composed of these phases. Martensite, primary troostite, and pearlite are transition products resulting from the direct transformation of austenite at different cooling rates. The constituent resulting from the most rapid cooling of carbon steel is martensite, which is the strongest, hardest, and least ductile of the transition constituents. Slower rates of cooling produce primary troostite and pearlite with increasing ductility, and decreasing strength and hardness.

Table V

Constituents in Steel



When martensite is obtained by very rapid cooling of carbon steels from temperatures above the critical range, its transformation to secondary troostite, sorbite, or the spheroidized structure is brought about by reheating the hardened steel to temperatures below the critical range. As the tempering temperatures are raised, the ductility of the heat-treated steel is increased, whereas the strength and hardness are decreased. It is therefore possible to produce in a given steel varying degrees of strength, hardness, and ductility by controlling the rate of cooling from the austenitic condition and by tempering the steel after hardening.

CONSTITUENTS IN SLOWLY COOLED CARBON STEEL

All carbon steels with less than 0.83 per cent carbon, when cooled slowly from temperatures above the critical range, are composed of grains of free ferrite and pearlite. When these steels are heated to temperatures above the line *A–E* in Fig. 28, the pearlite is changed to austenite, and the ferrite is gradually dissolved in the austenite as the temperature is raised. Above *C–E* only grains of austenite are present.

All carbon steels with over 0.83 per cent carbon when cooled slowly from temperatures above the critical range contain pearlite and free cementite at ordinary temperatures. When these steels are heated, the pearlite is changed to austenite above *E–B* in Fig. 28, and the cementite gradually dissolves in the austenite at higher temperatures. Above *E–D* these steels are composed entirely of austenite.

The changes in the constitution of carbon steels containing 0.20, 0.60, 0.83, and 1.10 per cent carbon, when these steels are heated from 1300 to 1650 degrees F., are indicated in Fig. 28. The relative grain sizes of these steels at different temperatures are shown within the circles. These diagrams apply particularly to coarse-grained steels in which the grains increase in size gradually at temperatures above the critical range for hypoeutectoid steels and at the lower critical temperatures for hypereutectoid steels. The austenite grains in some steels do not increase in size until above 1700 degrees F.; these steels are described as fine-grained steels.

The proportions of the constituents in slowly cooled carbon steels are shown in Fig. 37. Only pearlite is present in steel containing 0.83 per cent carbon. Those steels having less than 0.83 per cent carbon contain free ferrite in addition to pearlite. When the carbon content is greater than 0.83 per cent, excess cementite will be present as a network between the grains of pearlite as shown in Fig. 30.

The amounts of the structural constituents in slowly cooled carbon steel can be readily calculated. Steel containing 0.83 per cent carbon, after it has cooled slowly from above its critical temperature, is composed entirely of pearlite. In steels containing less than 0.83 per cent carbon, the proportion of pearlite is dependent directly upon the carbon content.

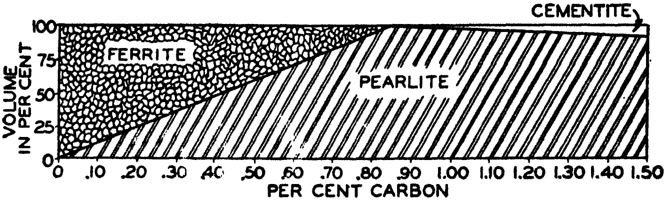


FIG. 37—CONSTITUENTS IN FULL-ANNEALED CARBON STEELS

The percentage of pearlite in any steel in this group is determined by dividing its carbon content by 0.83 and multiplying by 100. The percentage of the remaining material, ferrite, will then be equal to 100 minus the percentage of pearlite.

To find the percentage of each of the constituents in a carbon steel containing 0.66 per cent carbon, after cooling slowly from 1450 degrees F.:

$$\frac{0.66}{0.83} \times 100 = 80 \text{ per cent pearlite}$$

$$100 - 80 = 20 \text{ per cent free ferrite}$$

The constituents in slowly cooled carbon steels having over 0.83 per cent carbon are pearlite and free cementite. The percentage of pearlite in any of these steels can be found by using the following formula:

$$\frac{6.67 - \text{carbon in per cent}}{6.67 - 0.83} \times 100 = \text{percentage pearlite}$$

To find the percentage of each of the constituents in a carbon steel containing 1.20 per cent carbon after cooling slowly from 1625 degrees F.:

$$\frac{6.67 - 1.20}{5.84} \times 100 = 94 \text{ per cent pearlite}$$

$$100 - 94 = 6 \text{ per cent free cementite}$$

REVIEW QUESTIONS

1. Define cementite, and state the conditions under which this constituent is found in carbon steels.
2. What are the properties of martensite?
3. How is the sorbitic structure produced in constructional steels?
4. Describe the appearance of pearlite at high and low magnification.
5. Compare the ductility of the three secondary constituents resulting from the transformation of martensite.
6. Account for the change in hardness of slowly cooled carbon steels with increasing carbon contents.
7. Under what conditions is it possible to obtain a structure composed of martensite and cementite?
8. Explain the difference in the hardness of pieces of carbon steel containing 0.45 per cent carbon after cooling rapidly from 1375 and 1500 degrees F.
9. On the basis of the proportions and properties of its microconstituents, determine the tensile strength of slowly cooled carbon steel containing 0.55 per cent carbon.
10. Find the percentage of each of the constituents in a carbon steel containing 1.25 per cent carbon after cooling slowly from 1420 degrees F.

CHAPTER VI

THE EFFECTS OF TEMPERATURE CHANGES AND MECHANICAL WORKING UPON THE GRAIN SIZE AND PROPERTIES OF STEEL

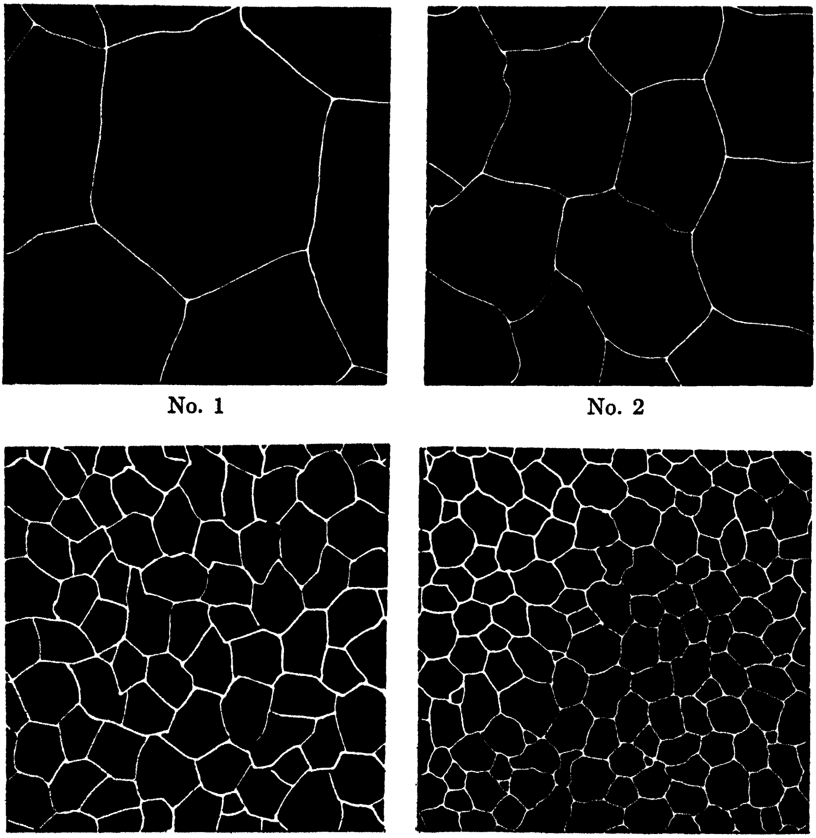
GRAIN SIZE OF STEEL—**Methods for Determining Grain Size—Effects of Grain Size on the Properties of Steel—Effects of Temperature Changes and Mechanical Working on Grain Size**—BURNING STEEL—MECHANICAL WORKING OF STEEL—**Hot Working**—Flow of Metal in Hot-Worked Steel—**Cold Working**

The properties of steel having a definite chemical composition are influenced somewhat by the practice used in its manufacture and to a large extent by the thermal and mechanical treatments to which it is later subjected. These treatments may alter the size of the grains in the steel and thereby affect its characteristics. The effects of heating, cooling, and mechanical working upon the grain size and properties of steel will now be considered.

GRAIN SIZE OF STEEL

Steel in the solid state is composed of crystalline grains which are plainly revealed in most fractured surfaces. Furthermore, a microscopic examination after polishing and etching a specimen of steel shows a granular structure. The size and shape of the grains depend upon the previous thermal and mechanical treatment of the steel.

When a piece of annealed steel is heated gradually from room temperature, no change takes place in the grain size until the lower critical temperature is reached, at which point, small grains of austenite are formed from the pearlite, and the free ferrite (or free cementite in steels containing over 0.83 per cent carbon) dissolves in the austenite as the temperature increases through the critical range. Only austenite remains at temperatures above the critical range. Refer to Fig. 28 in Chapter V. On continued heating to higher temperatures, the grain size increases very noticeably above a certain temperature which is known as the **coarsening temperature.** Several factors influence the temperature at which coarsening of the austenite grains takes place. In particular, the deoxidation treatment of steel with aluminum during its manufacture has a decided effect in raising the coarsening temperatures of steels. Some of the alloying elements, chiefly vanadium, molybdenum, and tungsten, have an influence in causing fine grains to be retained at relatively high temperatures. In addition to the influences of the deoxidation practice and the alloy content of the steel, the subsequent rolling temperatures and heat treatments change to some extent the coarsening temperature. A preliminary normalizing treatment will cause a lowering of the temperature at which coarse grains are developed.



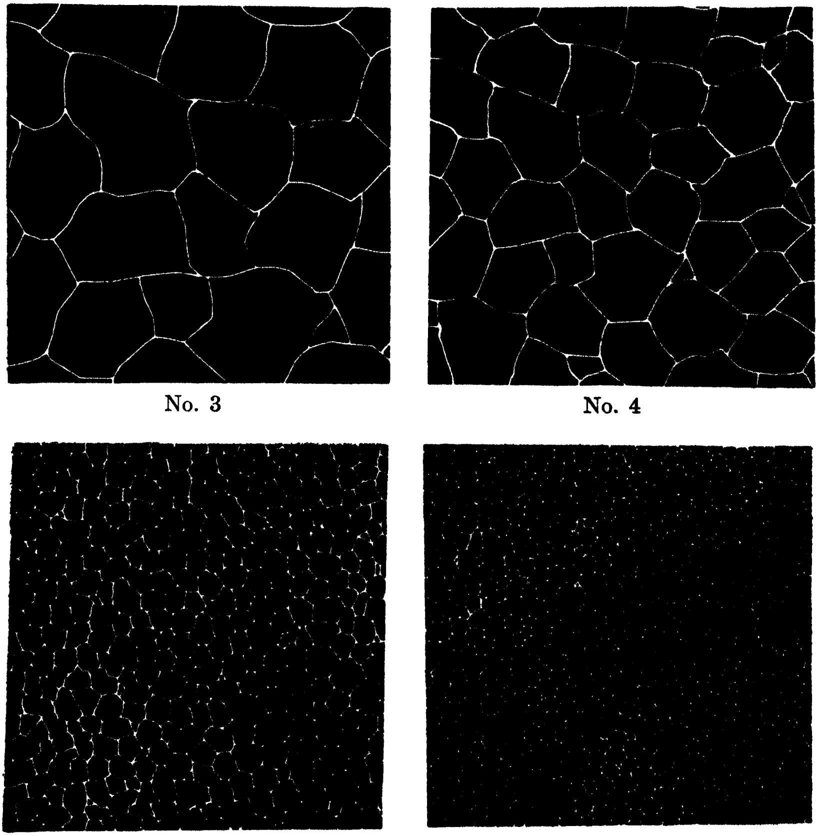
No. 1 No. 2

No. 5 No. 6

Fig. 38—Grain-Size Chart (*A.S.T.M.* Standards)

Methods for Determining Grain Size

The method for determining the grain size of steel, as proposed by the *American Society for Testing Materials*, requires carburizing the specimen at 1700 degrees F. for 8 hours and cooling slowly in the carburizing compound within the furnace. After cooling, a transverse section is prepared by polishing and etching, and is examined under a microscope at 100 magnifications. The size of the grains in the high-carbon case is compared with a chart listing a series of eight standard grain sizes. See Fig. 38. Steels are usually classified in ranges of grain size. Those sizes from 1 through 4 on the chart are designated as coarse grains, and those from 5 through 8 as fine grains. This test method (known also as the McQuaid-Ehn test) has been generally adopted by steel producers and consumers for classifying steels on the basis of grain size.



No. 3 No. 4

No. 7 No. 8

FIG. 38—GRAIN-SIZE CHART (*A.S.T.M.* STANDARDS)

The austenitic grain size may also be established by a fracture test in which specimens of steel are heated to temperatures within or above the critical range and quenched in water or oil. These specimens of hardened steel are then notched and fractured, after which the fractured surfaces are matched with a set of standard fracture specimens numbered from 1, the coarsest, to 10, the finest structure. The grain size of steel as determined by the fracture test coincides substantially with the grain size as judged microscopically on carburized specimens. The grain-coarsening temperature for any grade of steel may be found by heating specimens to different temperatures and noting the temperature at which coarse grains are retained after quenching.

It is generally agreed that a steel should not be reported as fine-grained or coarse-grained without taking into consideration the temperature at which it will be heat treated. That is, if a given steel is to be commercially heat treated for one hour at 1550 degrees F., the significant grain size is that developed under these conditions, and not as found by treatments involving longer times and higher temperatures. If the steel is to be carburized, the standard *A.S.T.M.* grain-size test is of definite value in classifying the steel.

Effects of Grain Size on the Properties of Steel

The austenitic grain size of steel of a given chemical composition has a decided influence on its physical properties and heat-treating characteristics. The effects of a relatively fine austenitic grain size in contrast to a coarser grain size for steels of the same chemical composition are summarized in Table VI. The choice of fine- or coarse-grained steels should be based on the specific requirements of the parts being manufactured. For some purposes, either type can be used satisfactorily. For other applications, a specific type should be employed. Fine-grained

TABLE VI

EFFECT OF GRAIN SIZE ON THE PROPERTIES OF STEELS

Property or Condition	Coarse-Grained Steel	Fine-Grained Steel
Hardenability	Deeper	Shallower
Impact Strength	Lower	Higher
Machinability	Better	Inferior
Quenching Cracks	Frequent	Usually absent
Distortion after Quenching	More	Less
Grinding Cracks	More	Less
Ductility at Same Hardness	Lower	Higher

steels are particularly advantageous for carburized parts which are quenched directly from the carburizing temperature. In general, fine-grained steels are less sensitive to variations in quenching temperatures, are less likely to be injured in hardening and grinding, and have greater ductility and impact strength than coarse-grained steels of the same composition. Fine-grained steels are less embrittled by cold working and therefore may be drawn deeper and show less defects in cold-forming operations than coarse-grained steels. On the other hand, coarse-grained steels harden deeper and machine more readily than fine-grained steels. "Hardenability," as used in Table VI, refers to the depth of hardening after steels of the same chemical composition, but of different austenitic grain sizes, have been quenched from their hardening temperatures.

Effects of Temperature Changes and Mechanical Working on Grain Size

The diagrams in Fig. 39 present graphically the effects of temperature changes and mechanical working upon the grain size of steel. The coordinates of each of the diagrams are time and temperature, and the circles represent the relative sizes of the grains resulting from different treatments.

When a piece of annealed steel composed of large grains of ferrite and pearlite is heated, the size of the grains is not changed until the lower critical temperature is reached. At this temperature (*B* in diagram I), the pearlite changes to austenite, and the coarse grains of ferrite gradually dissolve in the austenite as the temperature is raised through the critical range. The average minimum grain size is attained near the upper critical temperature (*C*), where the transformation to austenite is completed. When this piece of steel is cooled slowly from a temperature slightly above the critical range at *C*, small grains of ferrite and pearlite will be retained at room temperature, *D*.

When a piece of "coarse-grained" steel containing 0.15 per cent carbon is heated to temperatures considerably above the critical range, the grains of austenite increase in size as indicated from *C* to *E* in diagram II. The increase in grain size, which is the result of the merging of small grains into larger grains, is dependent upon the temperature to which the steel is heated. If this steel is cooled slowly from temperature *E*, large grains of ferrite with pearlite will be obtained as indicated at *F* in diagram II.

The changes in the size of the grains when a piece of "coarse-grained" carbon steel containing 0.45 per cent carbon is heated to high temperatures are shown in diagram III. The large grains of ferrite and pearlite are changed completely to small grains of austenite in passing through the critical range, and these grains increase in size when the steel is heated to higher temperatures. If this steel is cooled rapidly from the high temperature, coarse needles of martensite will be retained at room temperature as shown at *E* in diagram III. On the other hand, when a piece of "fine-grained" carbon steel containing 0.45 per cent carbon is heated above the critical range as shown in diagram IV, the small grains

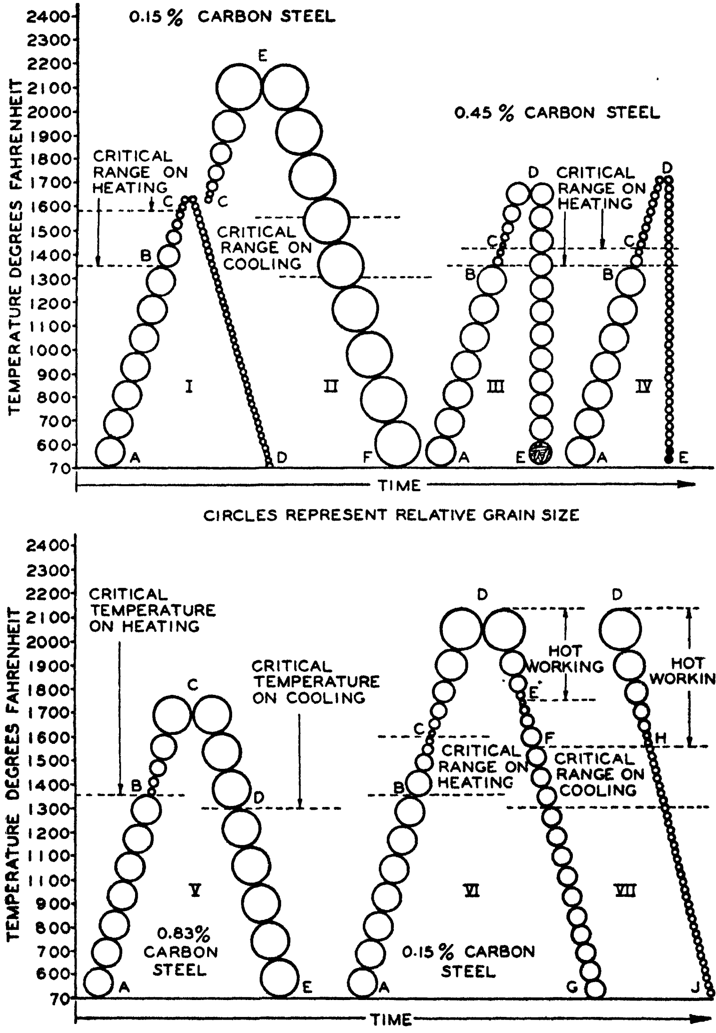

TEMPERATURE DEGREES FAHRENHEIT
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
70
0.15 % CARBON STEEL
CRITICAL RANGE ON HEATING
CRITICAL RANGE ON COOLING
A
B
C
D
E
F
I
II
0.45 % CARBON STEEL
CRITICAL RANGE ON HEATING
III
IV
TIME
CIRCLES REPRESENT RELATIVE GRAIN SIZE
CRITICAL TEMPERATURE ON HEATING
CRITICAL TEMPERATURE ON COOLING
0.83% CARBON STEEL
V
HOT WORKING
CRITICAL RANGE ON HEATING
CRITICAL RANGE ON COOLING
0.15 % CARBON STEEL
VI
VII
G
H
J
TIME

Fig. 39—Grain-Size Diagrams

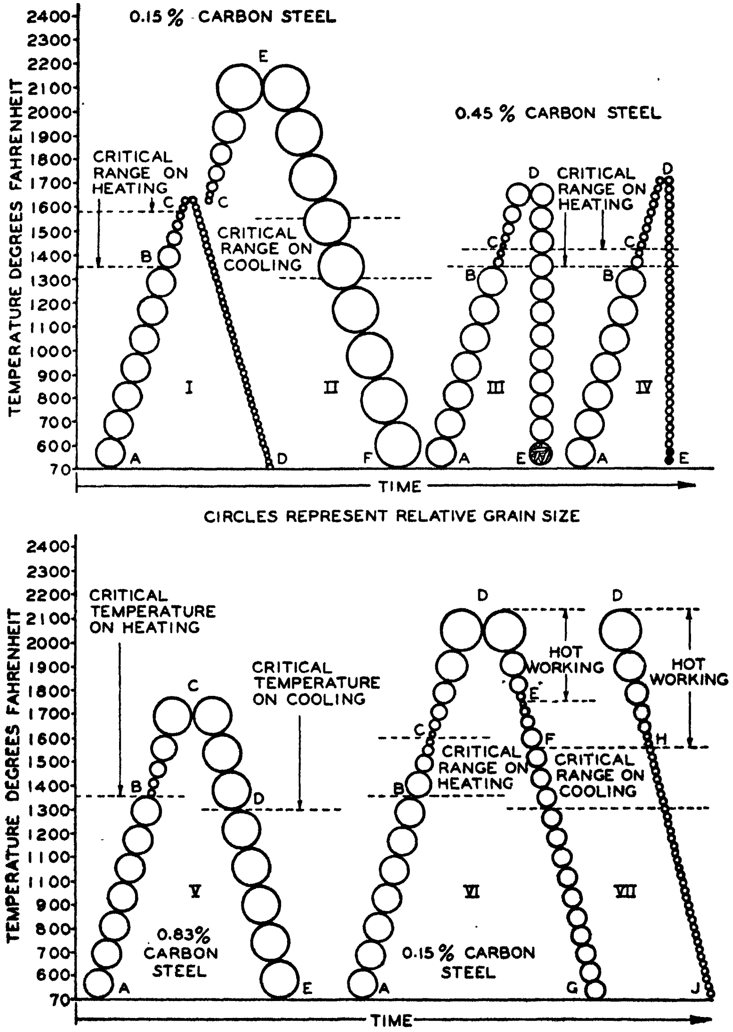
of austenite are not increased appreciably in size because the grain-coarsening temperature of this steel (above 1700 degrees F.) has not been exceeded. Small grains will therefore be retained at room temperature when this steel is cooled rapidly from any temperature below its grain-coarsening temperature.

When a piece of annealed carbon steel containing 0.83 per cent carbon is heated to high temperatures, the pearlite transforms to small grains of austenite at the critical temperature (about 1350 degrees F.), indicated at *B* in diagram V. As the temperature is raised to *C*, the grains of austenite increase in size above the coarsening temperature of the steel. If this steel is cooled slowly from the highest temperature (*C*), the grains of pearlite at room temperature will be practically the same size as the grains of austenite were at *C*. During cooling, the grains of austenite are changed to grains of pearlite at temperature *D*.

Steel which has been heated to temperatures just above the critical range is not sufficiently plastic to be worked to any great extent. Hence, the steel must be heated to higher temperatures to obtain the desired plasticity. The mechanical working of steel which has been heated to temperatures considerably above the critical range decreases the grain size as indicated in diagram VI and diagram VII. When the hot working is discontinued at temperatures above the coarsening temperature (in this case the upper critical temperature), the grains again increase in size as the steel cools to the coarsening temperature from *E* to *F* in diagram VI. When steel containing 0.15 per cent carbon is continually worked as its temperature drops to the critical range on cooling, a small grain size (ferrite and pearlite) will be retained at temperatures below the critical range. This condition is shown graphically in diagram VII. Steels containing over 0.83 per cent carbon are preferably hot worked down to temperatures approaching the lower critical temperature on cooling. The point *E* in diagram VI and *H* in diagram VII at which the hot working is discontinued are known as **finishing temperatures.**

The large grains normally present in steel which has been cooled slowly from temperatures considerably above its coarsening temperature become flattened out when this steel is mechanically worked at atmospheric temperatures. This change in the shape of the grains due to cold working is shown diagrammatically in Fig. 40, and is also indicated in Fig. 44.

It has been pointed out that small grains are obtained in steel having less than 0.83 per cent carbon by heating this steel to any temperature above its critical range but below its coarsening temperature, or by hot working the metal until its finishing temperature approaches the critical range on cooling. Also, a small grain structure is produced in a steel the critical range, and these grains increase in size when the steel is heated to higher temperatures. If this steel is cooled rapidly from the high temperature, coarse needles of martensite will be retained at room temperature as shown at *E* in diagram III. On the other hand, when a piece of "fine-grained" carbon steel containing 0.45 per cent carbon is heated above the critical range as shown in diagram IV, the small grains


2400
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70
TEMPERATURE DEGREES FAHRENHEIT
0.15 % CARBON STEEL
CRITICAL RANGE ON HEATING
CRITICAL RANGE ON COOLING
A
B
C
D
E
F
I
II
0.45 % CARBON STEEL
CRITICAL RANGE ON HEATING
III
IV
TIME
CIRCLES REPRESENT RELATIVE GRAIN SIZE
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1100
900
800
700
600
70
TEMPERATURE DEGREES FAHRENHEIT
CRITICAL TEMPERATURE ON HEATING
CRITICAL TEMPERATURE ON COOLING
V
0.83% CARBON STEEL
HOT WORKING
CRITICAL RANGE ON HEATING
CRITICAL RANGE ON COOLING
HOT WORKING
VI
VII
0.15 % CARBON STEEL
G
H
J
TIME

Fig. 39—Grain-Size Diagrams

of austenite are not increased appreciably in size because the grain-coarsening temperature of this steel (above 1700 degrees F.) has not been exceeded. Small grains will therefore be retained at room temperature when this steel is cooled rapidly from any temperature below its grain-coarsening temperature.

When a piece of annealed carbon steel containing 0.83 per cent carbon is heated to high temperatures, the pearlite transforms to small grains of austenite at the critical temperature (about 1350 degrees F.), indicated at *B* in diagram V. As the temperature is raised to *C*, the grains of austenite increase in size above the coarsening temperature of the steel. If this steel is cooled slowly from the highest temperature (*C*), the grains of pearlite at room temperature will be practically the same size as the grains of austenite were at *C*. During cooling, the grains of austenite are changed to grains of pearlite at temperature *D*.

Steel which has been heated to temperatures just above the critical range is not sufficiently plastic to be worked to any great extent. Hence, the steel must be heated to higher temperatures to obtain the desired plasticity. The mechanical working of steel which has been heated to temperatures considerably above the critical range decreases the grain size as indicated in diagram VI and diagram VII. When the hot working is discontinued at temperatures above the coarsening temperature (in this case the upper critical temperature), the grains again increase in size as the steel cools to the coarsening temperature from *E* to *F* in diagram VI. When steel containing 0.15 per cent carbon is continually worked as its temperature drops to the critical range on cooling, a small grain size (ferrite and pearlite) will be retained at temperatures below the critical range. This condition is shown graphically in diagram VII. Steels containing over 0.83 per cent carbon are preferably hot worked down to temperatures approaching the lower critical temperature on cooling. The point *E* in diagram VI and *H* in diagram VII at which the hot working is discontinued are known as **finishing temperatures.**

The large grains normally present in steel which has been cooled slowly from temperatures considerably above its coarsening temperature become flattened out when this steel is mechanically worked at atmospheric temperatures. This change in the shape of the grains due to cold working is shown diagrammatically in Fig. 40, and is also indicated in Fig. 44.

It has been pointed out that small grains are obtained in steel having less than 0.83 per cent carbon by heating this steel to any temperature above its critical range but below its coarsening temperature, or by hot working the metal until its finishing temperature approaches the critical range on cooling. Also, a small grain structure is produced in a steel containing 0.83 per cent carbon when this steel is heated above its critical temperature but below its coarsening temperature, or is mechanically worked from higher temperatures down to its critical temperature on cooling. To obtain small grains in carbon steels containing over 0.83 per cent carbon, these steels are heated just above the lower critical temperature or are hot worked from high temperatures down to the lower critical temperature on cooling.

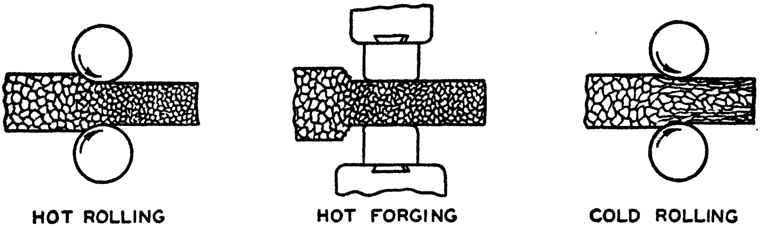


FIG. 40—CHANGES IN STRUCTURE DUE TO MECHANICAL WORKING

BURNING STEEL

Burning is the result of extreme overheating which causes the more fusible constituents in steel to melt and segregate at the grain boundaries or to separate from the metal. As oxidation proceeds rapidly at the temperatures which cause burning, in many cases the burned steel will also be severely oxidized. Steel which has been burned can be readily identified by the presence of voids at the grain boundaries or by its spongy structure. The desirable properties of steel can not be recovered after burning except by remelting.

MECHANICAL WORKING OF STEEL

The purposes of working steel are usually to change its form, dimensions, properties, or surface condition. All steel except that which is cast into the final shapes as steel castings is mechanically worked from the ingots down to the finished rolled or forged products. One of the important characteristics of steel is that of being plastic at high temperatures so that it can be readily changed in shape without rupture. The mechanical working of steel is described as hot working and cold working, depending on whether the metal is worked at temperatures above the critical range of the steel or at room temperature.

Hot Working

Steel is hot worked by hammering, pressing, rolling, upsetting, or bending the metal while it is at high temperatures. The forging range of temperatures for all carbon steels is shown in Fig. 45 in Chapter VII between the lines *M–N* and *C–E–B*. As the temperature of the steel is raised within the forging range, the resistance to deformation becomes less; hence, steel is heated to temperatures in the upper part of this range when a large amount of hot working is necessary. The heating and working operations, however, should be regulated so that the finishing temperature of the hot-worked steel is close to the upper critical temperature on cooling for steels containing less than 0.83 per cent carbon or close to the lower critical temperature on cooling for all steels containing over 0.83 per cent carbon. When this procedure is followed,

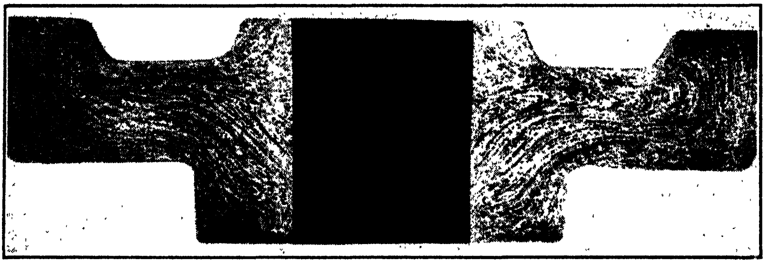
Courtesy of Erie Foundry Company

FIG. 41—STEAM FORGING HAMMER

the hot-working operation improves certain physical properties of the steel by producing grains of small size. See Table VI. The coarse grains in slowly cooled steel ingots are changed to smaller grains as the steel is worked in the rolling or forging operations.

Flow of Metal in Hot-Worked Steel—When a section of a piece of hot-worked steel is ground smooth and then immersed in an acid solution, the acid attacks the constituents selectively, leaving small ridges on the specimen. This effect is caused by the presence of inclusions which are oriented by the flow of the metal during hot working. Hence, the lines on the etched specimen known as **flow lines** indicate the direction of the flow of the metal during rolling or forging. A solution of 50 per cent concentrated hydrochloric acid and 50 per cent water at a temperature of 160 degrees F. is usually satisfactory to develop the flow lines.

The ductility and resistance to impact of the metal are less in a direction at right angles to the flow lines than parallel with them. Special care is therefore taken in the making of forgings for gears and other highly stressed parts to have the metal flow in the most favorable direction in all portions of the forgings. The radial flow of the metal in upset machine forgings is particularly advantageous for parts such as gear blanks. A section of an upset gear blank after deep etching is shown in Fig. 42. The direction of flow of the metal, which is plainly visible, is favorable for obtaining maximum strength in the teeth of the gear.



Courtesy of National Machinery Company

FIG. 42—SECTION OF UPSET GEAR BLANK, SHOWING FLOW LINES AFTER ETCHING

Cold Working

The operations by which steel is cold worked include rolling, upsetting, stamping, twisting, and drawing the metal through dies. These operations are usually carried out at room temperature. As steel can be cold worked only to a limited extent before it becomes too hard for further working at room temperature, cold working is employed chiefly as a finishing operation, following the shaping of the steel by hot working. Steel which is worked in the cold state is not subject to scaling, hence smooth surfaces are retained after cold working. Furthermore, the dimensions of cold-worked steel do not change after the cold-working operations. Steel shafting, bars, strips, and sheets are often cold finished to obtain smooth surfaces and accurate dimensions.

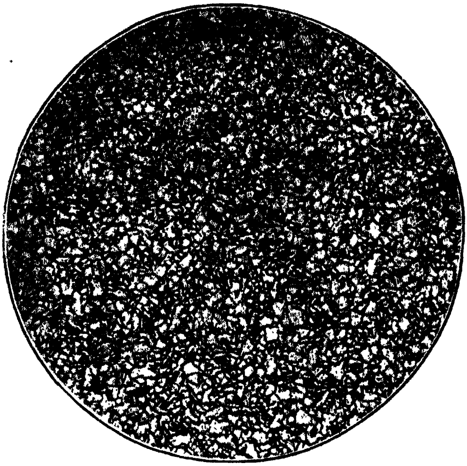


FIG. 43—HOT-WORKED STEEL, × 100

The small grain size is due to hot working. The specimen is a longitudinal section of low-carbon steel.

The effect of cold working on the structure of steel is to distort or elongate the grains in the direction of the flow of the metal. Compare Fig. 43 with Fig. 44. This distortion of the grains can be detected with the aid of the microscope only in material which has had drastic reductions. The amount of reduction ordinarily employed in cold drawing rods and bars is not sufficient to cause enough structural distortion to be apparent under the microscope. Cold working increases the tensile strength, yield strength, and hardness of steel, but lowers its ductility. As the grains are elongated in one direction by the cold working, the steel has directional properties. The tensile strength is greater when the load is applied in the direction of the flow of the metal than at right angles to this direction. Steel which has been cold worked is in a stressed condition as a result of the cold working, and any treat-

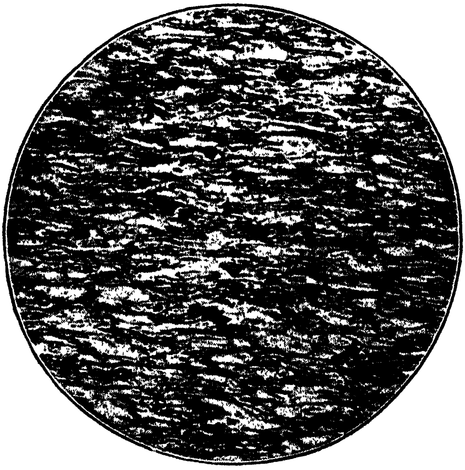


FIG. 44—COLD-WORKED STEEL, × 100

The grains are elongated in the direction of rolling. The specimen is a longitudinal section of low-carbon steel.

ment such as heating or machining a portion of the surface will cause a slight change in the shape of the piece. A keyway cut in one side of a cold-drawn steel shaft relieves the stress on this side, thus causing the shaft to bend with the convex surface on the side where the keyway was placed.

Low-carbon steels are machined more readily after being cold drawn. The improvement in machinability results from the decrease in ductility of the cold-worked metal, which causes the chips to break away from the edge of the cutting tool.

The increase in hardness resulting from cold working is described as **work hardening.** An excessive amount of cold working causes the steel to be brittle. Steel which is reduced in section or deformed can be softened by heating to temperatures in the vicinity of or slightly below the critical range. The greater the amount of cold working, the lower the annealing temperature at which an improvement can be obtained in the ductility of the steel. The effect of heating is to remove the stresses from cold-worked steel and to change the elongated grains to grains similar in shape to those in the steel before cold working.

When steel is mechanically worked at temperatures between 400 and 600 degrees F., the work-hardening effect is intensified to such an extent that the steel becomes very brittle. Consequently, mechanical working is usually not done within this range of temperature.

The properties given in Table VII were obtained from specimens of hot-rolled and cold-drawn carbon steel containing 0.20 per cent carbon.

TABLE VII

PROPERTIES OF CARBON STEEL

	Yield Point, Pounds per Square Inch	Tensile Strength, Pounds per Square Inch	Elongation, Per Cent in 2 Inches	Reduction of Area, Per Cent in 2 Inches	Brinell Hardness Number
Hot-Rolled Steel...	44,000	62,000	34	60	137
Cold-Drawn Steel..	72,000	81,000	17	57	187

The increase in strength resulting from cold working is indicated in the table. The tests were made with the long axes of the specimens in the direction of the flow of the metal. In the use of certain products such as wires for musical instruments and wire cables, bars for reinforcing concrete, and shafting for transmitting power, the increased strength of cold-worked steel is particularly advantageous.

REVIEW QUESTIONS

1. What factors influence the grain-coarsening temperatures of steels?
2. How is the grain size of any steel determined?
3. What are the advantages of fine-grained steel over coarse-grained steel?
4. What conditions affect the temperature at which steels should be heated for hot working?
5. What practice should be followed in producing the smallest possible grain size in steel by hot working?
6. Explain the effects of burning steel and how this condition can be avoided.
7. How is the direction of flow of the metal in a forging determined?
8. What condition is produced in steel which has been mechanically worked at temperatures about 500 degrees F.?
9. What are the effects of cold working upon the structure and physical properties of steel?
10. What advantages are obtained from the cold finishing of steel?

CHAPTER VII

PROCESSES AND EQUIPMENT FOR WORKING STEEL

HOT-WORKING PROCESSES—**Heating Steel for Hot Working**—Forging Furnaces—**Hot-Forging Processes**—Power Hammers—Drop Forging—Hot Pressing—Forging Machines—**Hot-Rolling Processes**—Rolling Mill Practice—Die Rolling—Forge Rolling—Roll Piercing—Rolling and Welding Pipe—COLD-WORKING PROCESSES—**Cold-Rolling Process**—**Cold-Drawing Process**—**Cold-Pressing Process**

Mechanical working is necessary in the manufacture of all forms of steel except that which is cast directly into its final shapes. Parts which are too intricate or too large to be shaped by mechanical working are produced by pouring the steel into sand molds, and are known as **steel castings.** The largest proportion of the total production of steel is formed to shape by working the metal while it is in a very plastic state at high temperatures, and the products are known as **steel forgings** and **rolled-steel shapes.** Additional working of the steel is often carried out at atmospheric temperatures to obtain special characteristics. In the following discussion, the processes for mechanically working steel are grouped under hot-working and cold-working processes.

HOT-WORKING PROCESSES

The processes for hot working steel may be classified according to the method of applying the mechanical forces into forging processes and rolling processes. **Forging** consists of working the hot, plastic metal by the use of hammers, presses, and forging machines. In the **hot-rolling** processes, the steel is mechanically worked as it passes between rolls which compress and lengthen the material. All the processes used in hot working steel improve the quality of the metal by producing small grains when the working is done within the correct temperature range and is continued to suitable finishing temperatures.

Heating Steel for Hot Working

The atmosphere in the forging furnace or forge fire has an important bearing on the condition of the metal which is to be hot worked. If the atmosphere is strongly oxidizing, a thick scale will be formed on the steel, and there is also the possibility of the removal of some carbon, a condition described as **decarburization,** which will cause the steel to be soft at those surfaces where the carbon has been removed. As far as possible, a neutral atmosphere should be maintained in the forging furnace or forge fire.

Certain precautions should be observed when steel is heated in preparation for any of the hot-working processes. Steel expands when heated except in the critical range, and, unless the heat is supplied gradually, cracks will be produced as the result of stresses in the metal. The larger the section, and the higher the carbon content, the slower should be the rate of heating. Alloy steels are particularly sensitive to rapid heating and are often preheated slowly to about 1400 degrees F. before being exposed to the higher temperatures in a forging furnace. The recommended practice of the *American Society for Metals* is that plain carbon steels with 0.50 per cent carbon and less, in sizes up to 3 inches square, be heated for a minimum time of 5 minutes per inch of thickness.

It is important that pieces of steel be heated uniformly throughout before working. When the metal is at the correct forging temperature on the outside and at too low a temperature in the interior, the metal at the center will be injured by mechanical working. When the opposite conditions prevail, and the outside has cooled too much before working begins, cracks will be produced on the outside of the forging. Uniform heating of the steel from the center to the outside is obtained by a uniform exposure of the steel to the hot gases within the furnace and by holding for a sufficient time to allow the heat to penetrate to the center.

As a rule, steel which is to be mechanically worked is heated only to that temperature which will give sufficient plasticity for working the metal to the desired shape. When considerable change of section is necessary, high temperatures are preferred. The **forging range** of temperatures for carbon steels is shown on the diagram in Fig. 45. At temperatures above the line *R–S*, the solid steel is gradually changed to the liquid state. Maximum forging temperatures are located below the line *R–S*. When carbon steels are heated to temperatures higher than those indicated by the line *M–N*, the metal may become permanently injured by burning. As a rule, the lowest temperatures at which carbon steels are hot worked are indicated on the line *C–E–B* in Fig. 45.

Forging Furnaces—Several types of furnaces are used for heating steel in preparation for forging. The box or batch type of furnace with a large door opening in front is built in any size to accommodate the work that is to be heated. These furnaces are usually constructed of a steel frame lined with insulating and refractory brick. One or more burners for gas or oil are provided on the sides, and the products of combustion come in contact with the metal being heated. Forging furnaces should be sufficiently large to allow proper combustion of the fuel and to obtain uniform heating of the work.

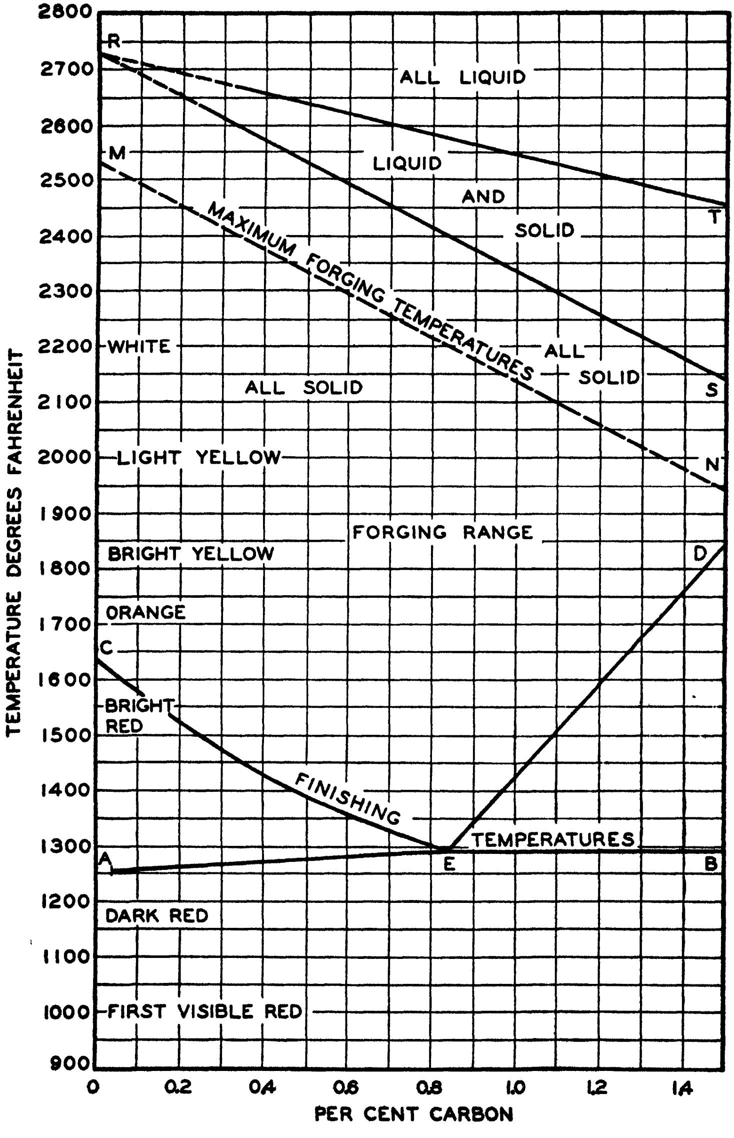


Fig. 45—Forging Range for Carbon Steels

For heating bars at one end only for drop forgings, or other forging operations, the slot-type furnace is commonly employed. The construction of this furnace is shown in Fig. 46. The steel bars are inserted through the slot at the front of the furnace and are removed intermittently when the desired forging temperature is reached. The position and number of burners as well as the size of the slot opening are dependent upon the capacity of the furnace and the maximum size of stock to be heated.

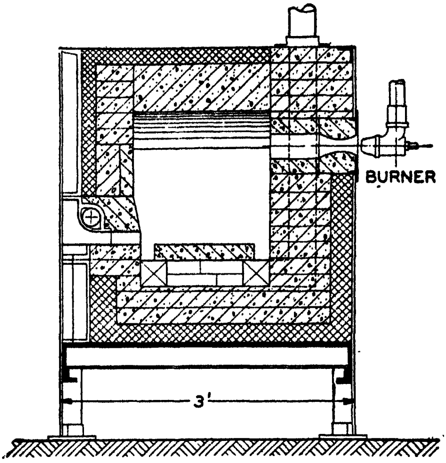


FIG. 46—CROSS SECTION OF FORGING FURNACE

Furnaces equipped with rotating hearths are sometimes used for heating large numbers of pieces of steel for forgings. The speed of rotation of the hearth is adjusted so that the work will be heated sufficiently after one or more revolutions. The clearance space between the hearth and the side wall is usually sealed with loose sand.

The continuous type of furnace equipped with a mechanical pusher may be used for operations requiring large production. See Fig. 86 in Chapter IX. The pieces of steel are charged at one end, are conveyed through the furnace, and are removed at the other end at the correct temperature for forging.

Hot-Forging Processes

The operations required in the making of steel forgings are drawing out, upsetting, expanding, punching, and shearing. All these operations are exemplified in the Laboratory Assignments which are appended to this text. In forging practice, the force of the hammer blows is regulated according to the thickness of the material being worked. Stock with a large cross section requires heavy blows to properly work the metal to the center.

When a round bar of steel is hot worked on the face of an anvil with a flat-faced tool or between flat dies in a power-operated hammer, the effect of the vertical forces is to cause the metal to draw away from the center. If the hot working is continued with constant rotation of the bar in an approximately cylindrical shape, the metal will rupture at the center. Forging operations should be conducted with the metal always in compression. In drawing out a large round to a bar of smaller diameter, the piece is first forged square and is reduced in this shape to about the desired size. The next step is to forge the corners to an octagonal shape and then to a round section with the desired dimensions.

When only a few small parts are required, hand forging is commonly employed; in this practice, the desired shapes are obtained by working the hot metal on an anvil with the hand hammer and other tools. Some of the tools used in hand forgings are illustrated in the Laboratory Assignments. The forging of large sections of metal requires the use of power-operated equipment. Also, the production of large numbers of forged parts is accomplished by power-driven machines equipped with special dies.

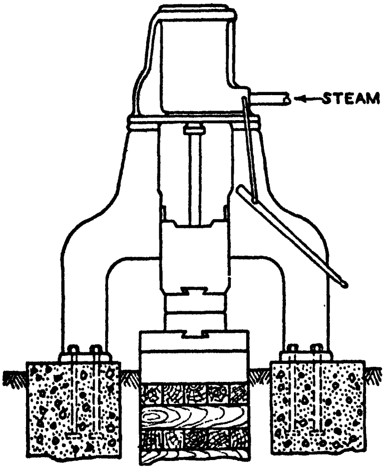
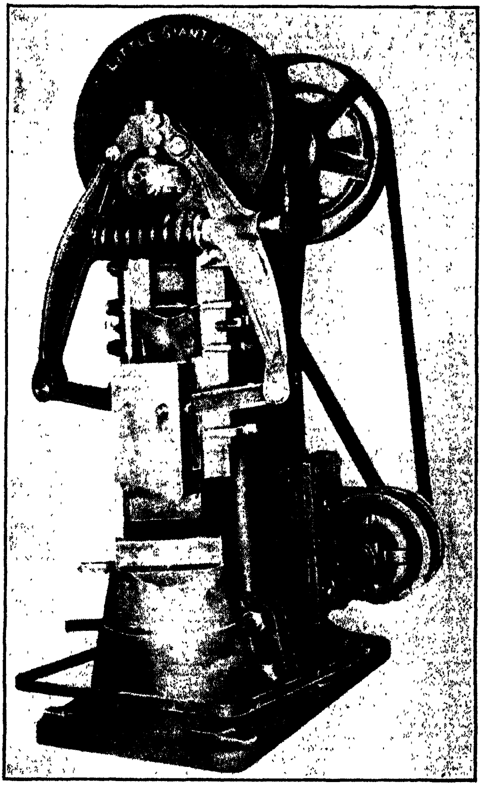


FIG. 47—STEAM FORGING HAMMER

Power Hammers—The general classification of power hammers includes (1) forging hammers and (2) drop hammers. The anvil block of a forging hammer is built on a foundation separate from the frames (see Fig. 47) so that the shock of the hammer blows will be cushioned by this foundation and will not be transmitted to the frames. On the other hand, the anvil of a drop-forge hammer is attached to the frames (see Fig. 52) to permit accurate alignment of the upper and lower dies. Furthermore, forging hammers may be constructed with single frames or double frames. Greater freedom of operation is permitted with the single-frame construction, although large hammers must have two frames to obtain the necessary rigidity. Steam-operated forging hammers are employed for a variety of work usually on large sections of steel. See Fig. 41 in Chapter VI. The sizes of these hammers are designated by the total weight of the ram, piston, and rod. Steam forging hammers are built in sizes of 600 to 80,000 pounds.

Forging hammers of the type shown in Fig. 48 are used commonly in forge shops for jobbing work. These hammers are built in sizes for forging material up to 7 inches in diameter, and are rated on the basis of the weight of the ram, which varies from 25 to 500 pounds. In the design shown in Fig. 48, the ram and the crank are connected by links and a spring which aid in increasing the force of the blows. The spring mechanism also makes possible blows of variable length which is necessary as the thickness of the stock decreases. The movement of the ram is started, stopped, and regulated by a foot treadle at the base of the hammer.

The forging hammer shown in Fig. 49, known as a **helve hammer,** is well adapted for general forging work where the size of stock is changed frequently. The ram of this hammer moves vertically in guides and is actuated by a wooden beam or helve. An adjustable eccentric on the main shaft operates the helve through rubber cushions which provide the snap and elasticity to the hammer blows. Pressure on the foot treadle, which extends around the front and sides of the hammer, causes the idler pulley to take up the slack in the running belt and starts the ram. As the speed increases, the force of the blows becomes greater.

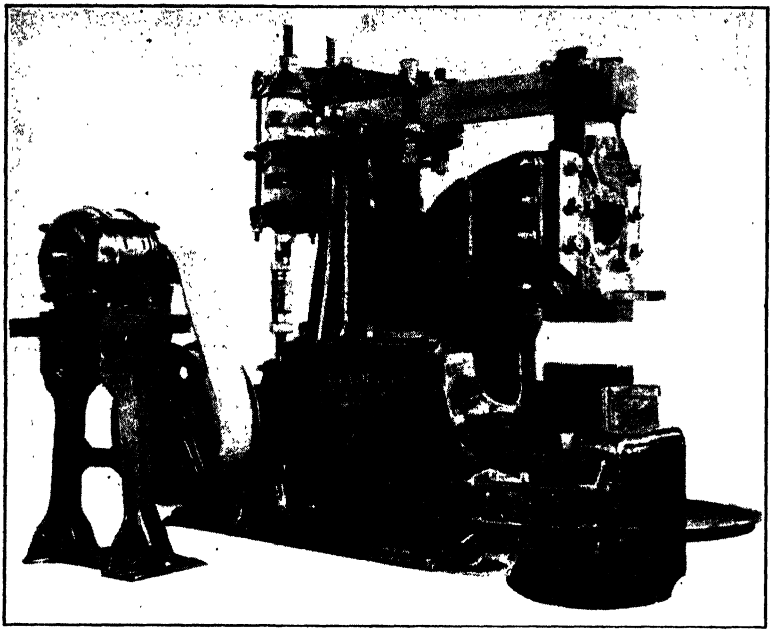


Courtesy of Little Giant Company

FIG. 48—COMPACT FORGING HAMMER

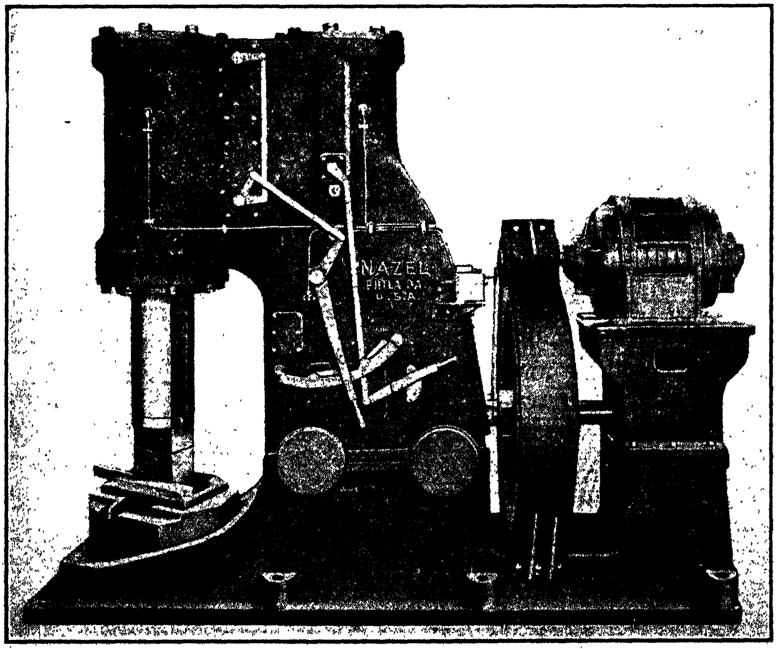
The forging hammer illustrated in Fig. 50 is operated by compressed air from a compressor which is contained in the frame of the hammer. This compressor is driven by an electric motor, and the air is delivered through valves into the ram or working cylinder of the hammer. When the valves are opened by means of a hand lever or foot treadle, the ram begins to operate. Light, medium, or hard blows are struck by regulating the movement of the valves. The hammer shown in Fig. 50 will deliver 100 blows per minute and will forge steel up to 13 inches in diameter.

The two types of power hammers used in making drop forgings are the steam or double-acting hammer, and the board or gravity hammer. The **steam drop hammer** illustrated in Fig. 51 has a large anvil block to which the heavy side frames are attached. The weight of the anvil is



Courtesy of C. C. Bradley & Son

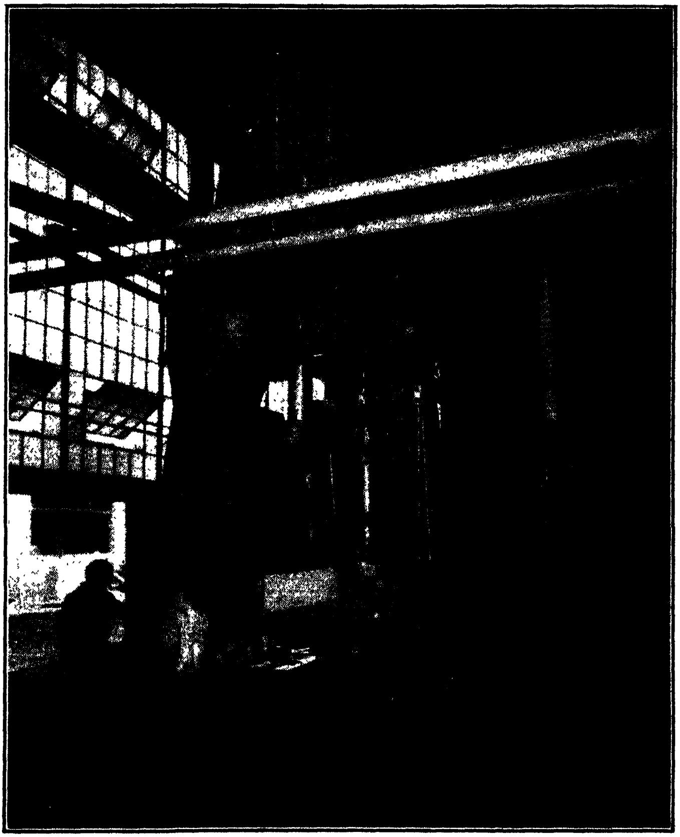
FIG. 49—HELVE HAMMER



Courtesy of Nazel Engineering and Machine Works

FIG. 50—FORGING HAMMER

about twenty times the total weight of the moving parts. A cylinder is mounted at the top of the frames, and the ram is securely fastened to the piston rod. The movement of the ram is controlled by admitting steam on either side of the piston. With slight changes in the valves, these hammers can be operated with compressed air. Steam drop hammers are rated on the basis of the combined weights of the ram, piston rod, and piston. Many sizes of hammers ranging from 500 to 50,000 pounds are employed in the drop-forge industry.



Courtesy of Alliance Machinery Company

FIG. 51—STEAM DROP HAMMER

The ram of the **board drop hammer** shown in Fig. 52 is attached to three wooden boards (usually of straight-grained maple free of knots) which extend upward between two metal rolls driven by belts from a line shaft. Other designs are operated directly from electric motors. The ram is raised by bringing the rolls in contact with the boards, and is released by separating the rolls. One of the roll shafts is supported in eccentric bushings and is moved by cams and levers on the hammer. The top die is keyed to the ram and the bottom die is keyed to the anvil cap or sow block which is securely fastened to the anvil. The purpose of the sow block is to protect the anvil from wear and to provide a movable part which can be resurfaced when necessary. Also, the ram can be removed from the hammer for machining when this is required. The force of the impact is dependent upon the combined weights of the falling parts. These hammers are used with capacities up to 8,000 pounds.

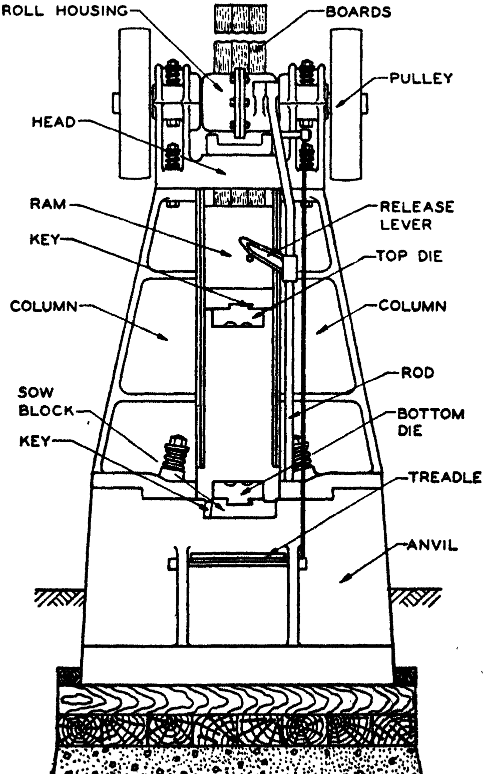
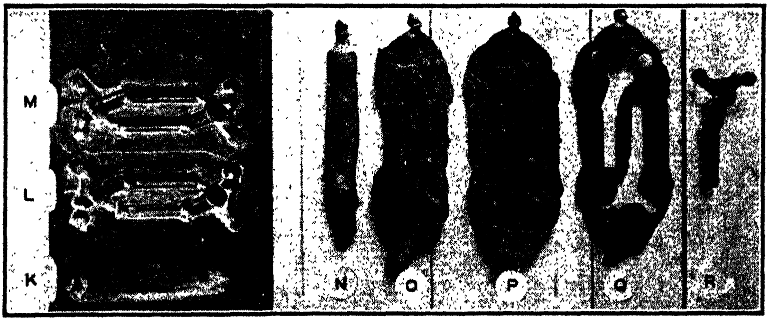


FIG. 52—BOARD DROP HAMMER

The selection of a suitable type of drop hammer for a given class of work depends upon the sizes and quantities of forgings to be made, as well as upon the availability of steam or other sources of power. A board drop hammer is not as well suited to the making of large forgings as the steam hammer. The steam drop hammer has much greater flexibility in operation than the board drop hammer. On comparable classes of work, the steam hammer is usually more productive than the board hammer. The total investment in equipment for board drop hammers is less than for steam drop hammers, for the same amount of production.

Drop Forging—In this process, a piece of steel which has been heated throughout to the forging temperature or a bar of steel which has been heated at one end is hammered into impressions formed in two heat-treated steel dies. The bottom die is secured to the anvil, and the upper die is attached to the ram of the drop hammer as shown in Fig. 52. The dies are matched so that the impressions in each are in perfect alignment. These dies are made of a superior grade of plain carbon or alloy steel which is heat treated to the desired hardness usually before the impressions are cut in the blocks. The machining of the impressions in the blocks is known as die sinking.

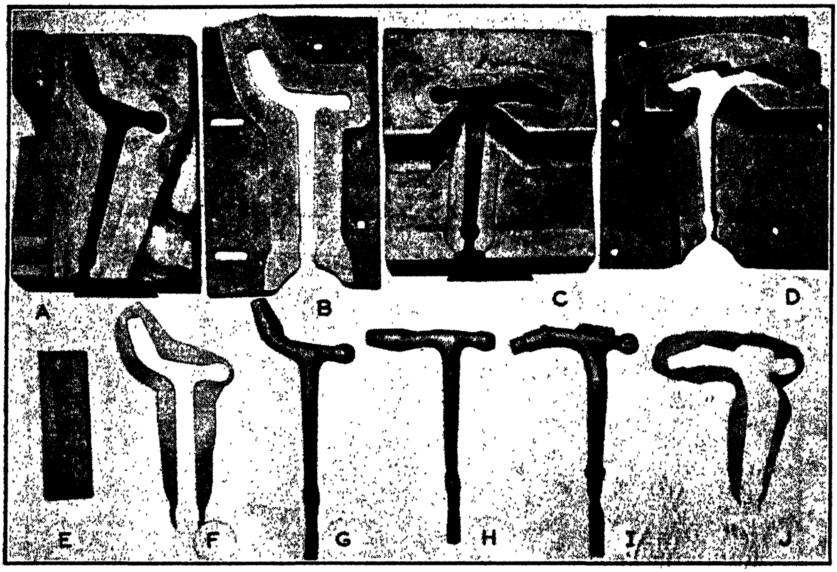


Courtesy of A. M. Steever

FIG. 53—DROP FORGE DIE AND FORGINGS

The steel for drop forgings is heated to a highly plastic state in a furnace which is located near the hammer. After the metal has been heated, it is placed in the successive impressions in the die blocks. The repeated blows of the hammer force the plastic metal into the dies, and any additional metal is spread between the faces of the dies. Most of the metal in excess of that required to fill the last impression is forced into a channel around the impression for the forging. After each blow of the hammer, the forging is lifted out of the impressions in the bottom die to allow for the removal of scale. A jet of steam or compressed air is used to blow the scale away from the dies.

The first forging operation which is usually required in making drop forgings is reducing the size of the bar stock to rough dimensions; this operation is known as the break-down or roll and is done in the break-down impression shown at *K* in Fig. 53. The stock after this step is shown at *N*. The second operation is to form the hot metal to the rough shape as shown at *O*. This operation is done in the rougher or blocker impression shown at *L*. The third operation is to work the metal further to finished dimensions; this is accomplished in the finisher impression shown at *M*. The three progressive forming operations are done in one set of dies in one hammer with one heating of the metal. It is now necessary to trim the excess metal called the flash (*Q*) from the forging (*R*). This operation is usually done in a mechanical press which is located near the drop hammer. Two trimming dies are shown at *B* and *D* in Fig. 54. The punches for the trimming dies are not shown. Other operations such as bending the forgings are required with some designs. Note that forging (*G*) in Fig. 54 is bent before being placed in the finishing die (*C*). The drop-forging process makes possible the rapid produc-



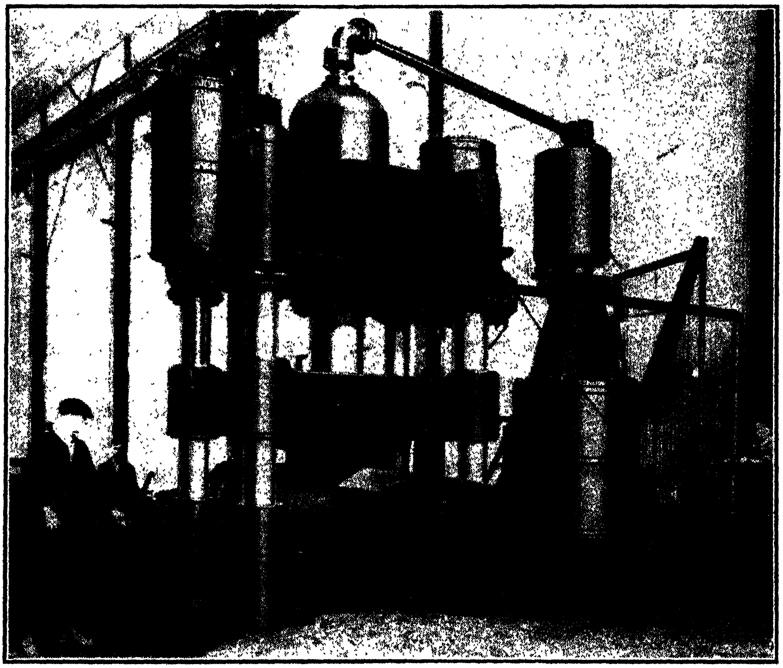
Courtesy of J. H. Williams Company

FIG. 54—DROP FORGE DIES AND FORGINGS

A—Break-down die.
B—Break-down trimmer die.
C—Finish forging die.
D—Finish trimmer die.
E—Bar stock used in die *A*.
F—Flash from trimmer die *B*.
G—Forging from die *B*.
H—Forging after bending.
I—Finished forging.
J—Flash from trimmer die *D*.

tion of large numbers of duplicate parts. Tools, gear blanks, crankshafts, connecting rods, and a great variety of machine parts are produced in this way.

Hot Pressing—The high cost of maintenance as well as the difficulties resulting from vibration during the operation of large hammers restrict the size of this equipment. In the forging of large sections of metal such as those required in the manufacture of guns and large machine parts, hydraulic presses are most satisfactory. The forging press shown in Fig. 55 has a hydraulic cylinder supported on steel columns which are anchored to a heavy base. The crosshead is attached to the piston and carries the upper forming die. On top of the base is the anvil which supports the lower forming die. In the unit at the right in Fig. 55, steam is used to compress the water to the high pressures required in the cylinder of the press. The ram is raised by admitting steam to two cylinders, one on each side of the press. Enormous pressures can be exerted on the material being worked by admitting water

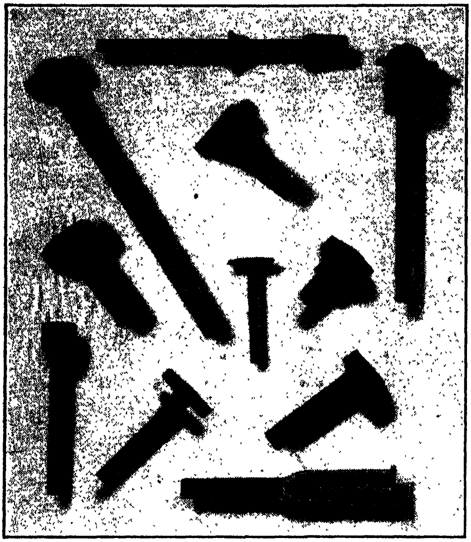


Courtesy of Morgan Engineering Company

FIG. 55—STEAM-HYDRAULIC FORGING PRESS

Capacity 1000 tons, maximum stroke 42 inches, distance between front columns 5 feet and 7 inches. Columns are attached to base.

under pressure to the top of the cylinder. The effects produced by the forging press differ from the effects of hammer blows. The action of the press is so slow that a kneading of the metal takes place, and the grain structure of the metal is refined at considerable depth.

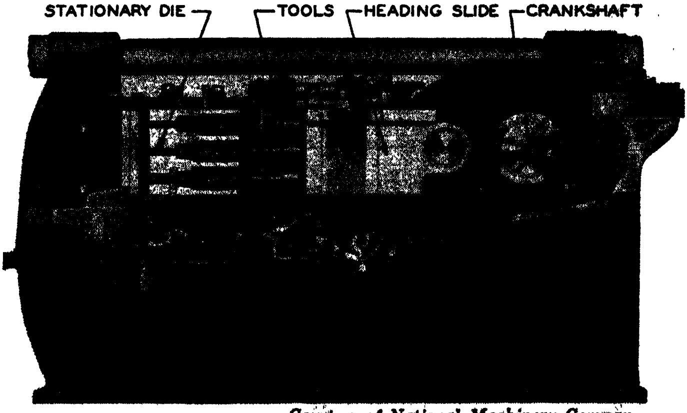


Courtesy of National Machinery Company

FIG. 56—STEEL PARTS MADE ON FORGING MACHINE

Forging Machines—Many different shapes and sizes of upset and pierced forgings are produced by hot working steel in forging machines. Some examples of these forgings are shown in Fig. 56. In making machine forgings, the end of a bar of steel of uniform cross section, usually round, is subjected to a succession of upsetting and piercing operations.

The forging machine illustrated in Fig. 57 is constructed of a heavy horizontal frame with a crankshaft at one end coupled to a heading slide by means of a short connecting rod. The heading slide moves horizon-



Courtesy of National Machinery Company

FIG. 57—SECTION OF FORGING MACHINE

tally and carries the upsetting and piercing tools. Two die blocks are provided, one stationary and the other mounted on a slide so that it can be moved transversely at right angles to the direction of motion of the tools. When the machine is being used, the heated end of a bar of steel is gripped by the dies while the upsetting tool is forced against the end of the stock, causing it to fill the recess in the dies. Other upsetting and piercing operations follow, and the steel is thus formed to the desired shape as the bar is transferred successively from the top to the bottom impression in the dies.

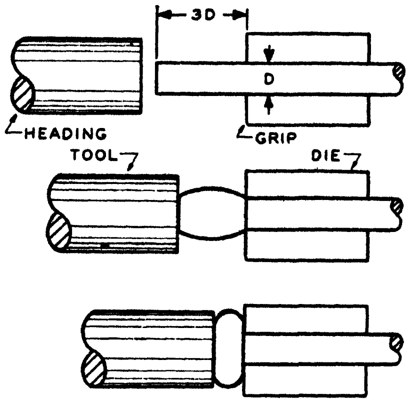


Fig. 58—Upset Forging

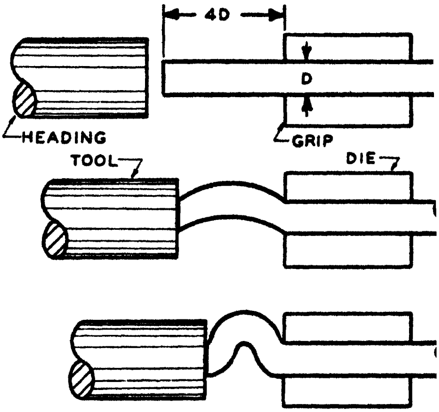


Fig. 59—Upset Forging

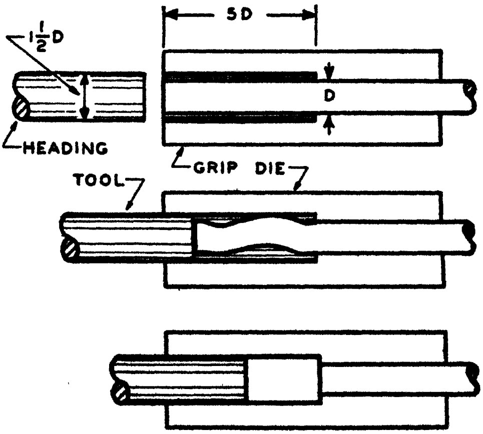


Fig. 60—Upset Forging

Certain rules relating to the making of upset forgings in forging machines have been prepared by the National Machinery Company. Rule 1 is as follows: The maximum length of unsupported stock that can be gathered or upset in one blow without injurious buckling is three times the diameter of the stock. See Fig. 58 and Fig. 59. Rule 2 is as follows: Lengths of stock more than three times the diameter can be gathered or upset in one blow provided the upset is contained in either the gripping die or the heading tool and the diameter of the upset made in that blow is not more than one and one-half times the diameter of the stock. This rule is illustrated in Fig. 60 and Fig. 61. Rule 3 is as follows: For upsets requiring a length of stock more than three times the diameter and in which the upset portion is one and one-half times the diameter, the length of unsupported stock beyond the face of the die must not exceed the diameter of the stock. If a longer unsupported length is used, the stock will buckle outside the dies as shown in Fig. 62.

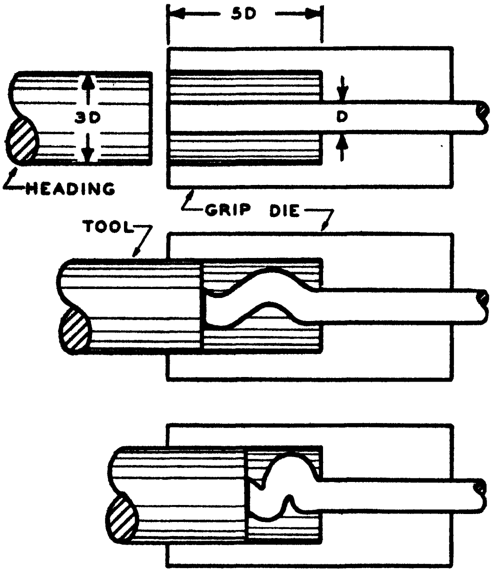


FIG. 61—UPSET FORGING

Hot-Rolling Processes

In the hot-rolling processes, steel in a hot plastic state is passed between two rolls revolving at the same speed but in opposite directions. As the material passes through the rolls, it is reduced in thickness and increased in length. The mechanical pressure exerted upon the steel during the rolling operations breaks up the original coarse grain structure, and thereby improves the properties of the metal. The grain size of the final product is dependent upon the temperature to which the metal was heated, the amount of hot working, and the temperature of the steel on completion of the rolling operations.

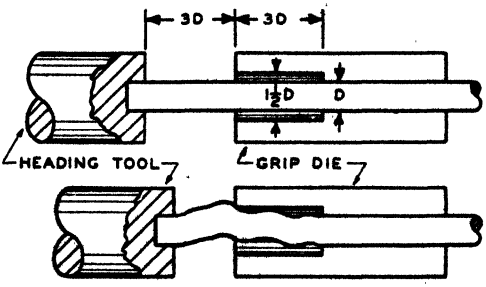
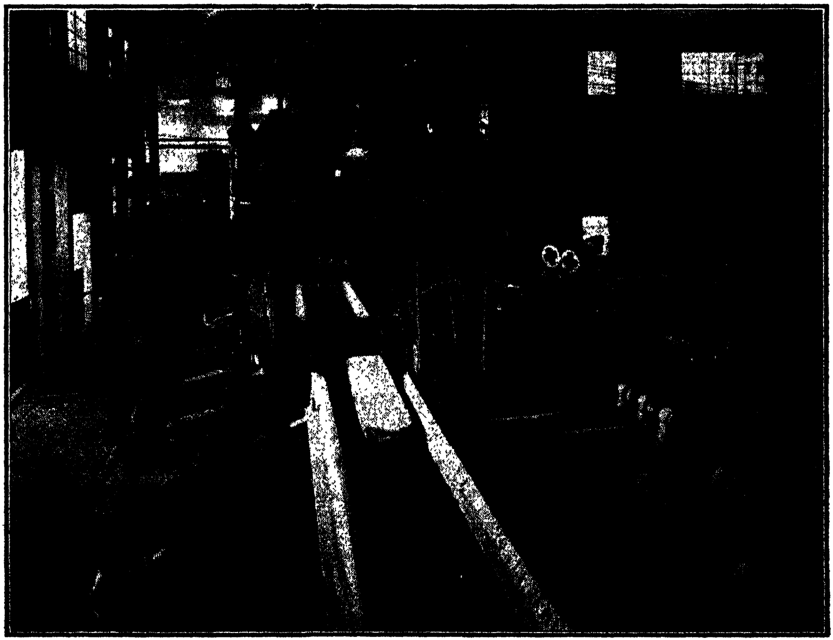


FIG. 62—UPSET FORGING

The forming of bars, plates, sheets, rails, angles, I-beams, and other structural sections requires many passes through plain or grooved rolls. In the die-rolling and forge-rolling processes, the rolls or segments of rolls have impressions cut on their surfaces which develop the desired shapes of the product.

Rolling Mill Practice—A large proportion of the total tonnage of steel consumed is processed in rolling mill operations. The hot working begins with the reduction of ingots which have been heated in soaking pits to the desired rolling temperature. Refer to Chapter I. The ingots are rolled on blooming mills between two grooved rolls, one directly above the other as shown in Fig. 63. The space between the rolls can be adjusted and the direction of rolling can be reversed for alternate trips or passes through the rolls. On each side of the mill are motor-driven roller conveyors on which the hot ingot is moved to and from the rolls. Devices known as manipulators are provided to turn the ingot, and side guards guide the ingot to any pass in the rolls.



Courtesy of Bethlehem Steel Company

FIG. 63—BLOOMING MILL

During the rolling of the ingot at the blooming mill, the ingot is frequently turned 90 degrees so that all surfaces of the ingot are in contact with the rolls and worked as uniformly as possible during the reduction. On a two-high blooming mill, the direction of rotation is reversed and the distance between the rolls is decreased after each pass of the ingot through the rolls. An ingot about 23 inches square can be rolled down to a bloom 6 inches square in about 17 passes, and in about 2 minutes.

A set of rolls and the housings in which they are mounted are known as a stand. Two or more stands arranged end on end are called a train. When the stands are placed one in front of another, this arrangement is known as a tandem or continuous mill. A mill which has two rolls in a stand is described as a two-high mill. Likewise, a three-high mill has three rolls, and a four-high mill has four rolls. Each roll in a three-high mill revolves continuously in one direction only, whereas, in two-high mills, the direction of the rolling may be in one direction only, or in opposite directions at different intervals, in which case they are known as reversing mills. In a three-high mill, the work travels in one direction between the middle and lower rolls, and in the opposite direction between the middle and upper rolls. To raise and lower the work as it passes back and forth through the rolls, lifts or tilting tables are provided on each side of a three-high mill. The top and bottom rolls in a four-high mill serve as stiffening or supporting rolls for smaller rolls which are in contact with the work. The smaller rolls are driven and the larger rolls run idle. Vertical rolls are provided on some stands to produce square edges on the rolled product.

For blooming mills and roughing stands of other mills where great strength is required, the rolls are made of cast steel with or without alloys. Some rolls, except those used for finishing, have roughened surfaces to increase the grip on the metal being rolled. Finishing rolls are usually made of chilled cast iron.

At some plants, ingots are rolled by passing continuously through four stands of blooming rolls. In each succeeding stand, the cross section is reduced, and between passes the piece is rotated 90 degrees so that the metal is worked on all sides. From the last stand of rolls, the bloom travels on a roller conveyor to a large shear where the ends are cropped off, and the piece may be cut into short lengths for convenience in handling. The cropping from the top of the ingot removes the portion which contains the pipe or shrinkage cavity, and the cropping from the bottom of the ingot squares that end of the bloom.

When the steel is to be used for bars, blooms are reduced in size on the original heat to billets by passing through a continuous series of rolls known as a billet mill. Between some of the passes, each bloom is turned so that different faces are subjected to the direct action of the rolls. The billet is then cut into shorter lengths which are reheated for further rolling in a series of two-high stands of rolls in the bar mill. After leaving the final set of rolls, the material is cooled on a bed, called a hot bed, and is then sawed or sheared to the desired lengths.

In the manufacture of plates, ingots are first reduced in size on slabbing mills, producing long flat pieces of steel. Slabbing mills are usually of the two-high reversing type provided with vertical or edging rolls. After the ends are cropped, the product from the ingot is cut into slabs of a size required by the plate mill. In some plants, the slabs are immediately conveyed to continuous hot-rolling mills; in others they are allowed to cool and are stored for future rolling. Records are kept of the heat of steel from which each slab was produced, and those slabs are selected which have the desired chemical composition for the plate to be rolled. Surface defects on the slabs are usually removed by pneumatic chippers or oxyacetylene scarfing torches. Reheating is done in continuous furnaces in which a cold slab, charged in at one end by a motor-driven pusher, forces a hot slab out of the other end of the furnace. In the continuous-type mill, the hot slabs, 3 to 6 inches in thickness and of various widths are rolled between flat rolls in a series of roughing and finishing mills with proper reduction in each stand to produce the desired thickness. When a three-high mill is used for all reductions from the slab to the finished plate, the middle roll of each stand is lowered or raised as the material is passed back and forth between the rolls. When the plate has been rolled to the desired thickness, it is carried forward on a roller table (see Fig. 64) to a roller straightening machine where it

Courtesy of Bethlehem Steel Company

FIG. 64—PLATE MILL

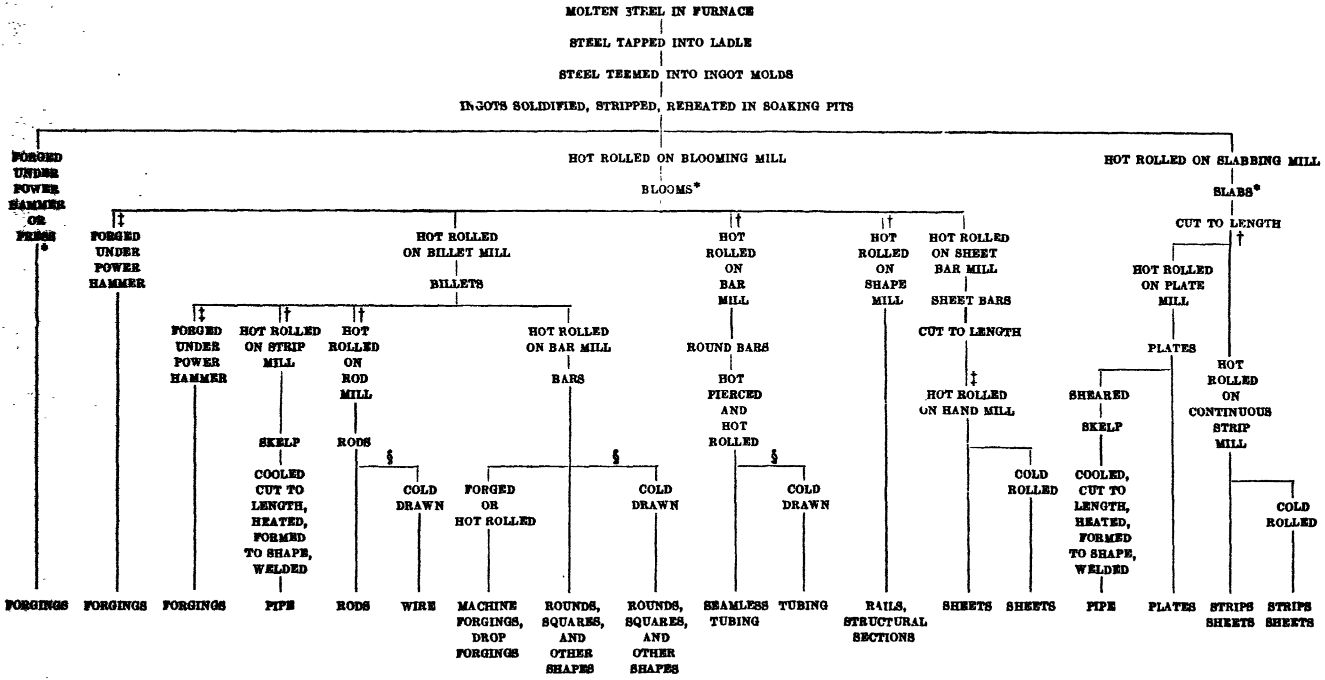
passes between two series of rolls, leaving the plate flat and straight. After the plates have cooled sufficiently, they are sheared to the required dimensions.

Large tonnages of sheet steel in many different grades and finishes are required to meet the demands of industry. The two methods for producing sheet steel are the pack rolling method, which is the older, and the continuous strip method, which is a more recent development. The material used in the pack rolling method is a semi-finished product known as sheet bars, which are obtained by rolling blooms to sections 8 to 16 inches wide, less than 1½ inches thick, and about 30 feet long. These bars are cut into lengths slightly greater than the width of the sheet to be rolled. The sheet bar multiples are heated in a furnace and, after reaching the desired temperature, are passed through a two-high stand of smooth rolls. After each pass, the piece is returned over the top roll for further reduction by decreasing the distance between the rolls. These operations are repeated until the metal becomes too cold for further rolling. Before reheating, the sheets known as break-downs are sometimes pickled to remove the scale and are then washed and dried. The break-downs are reheated, the proper number are placed together, and they are rolled again. From two to four break-downs are then placed in a pack, doubled by bending transversely, and reheated. This pack is passed through the rolls a number of times to reduce the thickness of the individual sheets and is then allowed to cool. For very thin sheets, the pack is again doubled, reheated, and rolled in the same mill. When they have cooled sufficiently, the packs are sheared all around and then opened. The sheets are usually annealed, pickled to remove the scale, washed in water, and dried. Sometimes the sheets are individually cold rolled between polished rolls to improve the surface and flatness.

In the continuous strip method of making sheet steel, slabs are hot rolled on roughing and finishing mills in tandem, the finishing stands being set on close centers (about 18 feet) so that one strip is in all finishing rolls at the same time. The roughing mill is usually preceded by a two-high stand of rolls to break up the scale on the surface of the slab. The first stand can be used to spread the slab to an increased width. After it is turned back 90 degrees, it is squeezed in a hydraulic press to straighten the edges. Some roughing stands, usually of the four-high type, are equipped with vertical edging rolls to maintain smooth edges and the desired thickness. In the roughing rolls, the thickness of the strip may be reduced to about one inch and the length increased to forty feet or more. From the last roughing stand, the hot strip is conveyed on rollers to the finishing stands. Each succeeding stand of rolls is

TABLE VIII

OUTLINE OF THE PRODUCTION OF WROUGHT-STEEL PRODUCTS


MOLTEN STEEL IN FURNACE
STEEL TAPPED INTO LADLE
STEEL TEEMED INTO INGOT MOLDS
INGOTS SOLIDIFIED, STRIPPED, REHEATED IN SOAKING PITS
FORGED UNDER POWER HAMMER OR PRESS *
HOT ROLLED ON BLOOMING MILL
BLOOMS*
HOT ROLLED ON SLABBING MILL
SLABS*
‡ FORGED UNDER POWER HAMMER
HOT ROLLED ON BILLET MILL
BILLETS
† HOT ROLLED ON BAR MILL
† HOT ROLLED ON SHAPE MILL
HOT ROLLED ON SHEET BAR MILL
SHEET BARS
CUT TO LENGTH
CUT TO LENGTH †
HOT ROLLED ON PLATE MILL
PLATES
‡ FORGED UNDER POWER HAMMER
† HOT ROLLED ON STRIP MILL
† HOT ROLLED ON ROD MILL
HOT ROLLED ON BAR MILL
BARS
ROUND BARS
‡ HOT ROLLED ON HAND MILL
SHEARED
SKELP
HOT ROLLED ON CONTINUOUS STRIP MILL
SKELP
RODS
§
COOLED CUT TO LENGTH, HEATED, FORMED TO SHAPE, WELDED
COLD DRAWN
FORGED OR HOT ROLLED
§
COLD DRAWN
HOT PIERCED AND HOT ROLLED
§
COLD DRAWN
COLD ROLLED
COOLED, CUT TO LENGTH, HEATED, FORMED TO SHAPE, WELDED
COLD ROLLED
FORGINGS
FORGINGS
FORGINGS
PIPE
RODS
WIRE
MACHINE FORGINGS, DROP FORGINGS
ROUNDS, SQUARES, AND OTHER SHAPES
ROUNDS, SQUARES, AND OTHER SHAPES
SEAMLESS TUBING
TUBING
RAILS, STRUCTURAL SECTIONS
SHEETS
SHEETS
PIPE
PLATES
STRIPS SHEETS
STRIPS SHEETS

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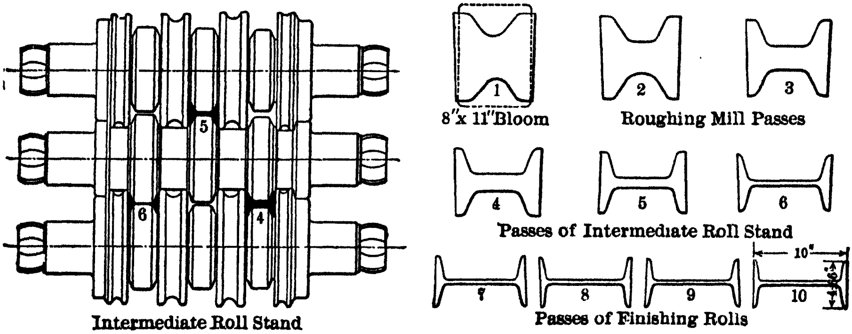
* Cropped on ends to remove defective material.

† May be hot worked continuously with initial heat; or cooled, chipped to remove surface defects, and reheated; or cooled and reheated.

‡ Usually cooled, chipped to remove surface defects, and reheated.

§ Pickled in acid solution to remove scale, washed in water, dipped in lime bath, and dried.

operated at greater speed to compensate for the rapidly increasing length of the strip. After each strip is delivered from the last finishing stand, it is either wound into coils, or cut to size, flattened by leveling, and piled. About the lightest sheets which can be hot rolled by the continuous strip method is 18 gage (0.050 inch in thickness). If thinner gages are required, the strip from the hot-rolling mills is cooled, pickled to remove the scale, and finally cold reduced in a tandem cold-rolling mill. See Fig. 26 in Chapter IV. When the steel is to be used in separate flat sheets, the coiled material is trimmed and sheared to the desired sizes. The sheets are then annealed to restore ductility. The annealed sheets may be shipped dead soft or may be given a skin pass between polished rolls to improve the properties.



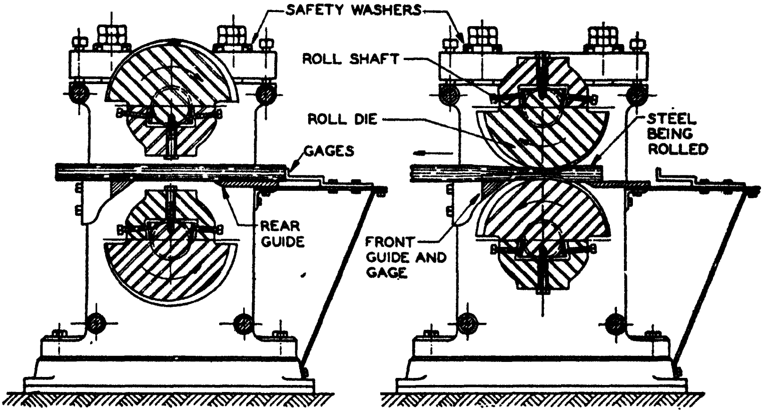
From Johnson's "Materials of Construction," 8th Ed., John Wiley & Sons

FIG. 65—TYPICAL ROLL PASSES IN FORMING A 10-INCH I-BEAM

In the rolling of structural sections and rails, blooms are usually reheated and are passed through a series of passes in rolls. The first pass has approximately the dimensions and shape of the bloom and each succeeding pass approaches the shape of the finished product. To produce a standard 10-inch I-beam from a bloom 8 by 10 inches, 10 passes are necessary to roll the finished shape, as illustrated in Fig. 65. The long lengths of structural sections from the finishing pass are cut to length on a hot saw, cooled on hot beds, straightened, and finally inspected before shipment.

Die Rolling—The most rapid method for producing steel parts with variable sections is by the die-rolling process in which the hot steel is passed continuously through a set of rolls having the developed shape of the part sunk in their surfaces. As the heated bar passes through the die-rolling mill, it is formed into a string of die-rolled forgings, containing as many as fifty pieces to the bar. After the bars have cooled, they are sheared into separate blanks which are then delivered to trimming presses and grinding machines for removing the surplus metal. Some of the products obtained by the die-rolling process are shafts, levers, and tie rods.

Forge Rolling—This process consists of heating the stock which is to be worked and passing it between segments of rolls which are grooved to conform to the desired shape of the piece. The number of grooves in the roll dies and hence the number of passes necessary to complete the piece depend on the amount of reduction to be effected. The machine used in this process is illustrated in Fig. 66. The semi-cylindrical roll dies are carried on two shafts which revolve continuously. When the dies are in the open position, the stock is inserted between the front guides until it comes in contact with the back gage. As the dies rotate, the stock is rolled towards the front of the machine, as shown at the right in Fig. 66, and is then placed in the next position for further reduction. Although many steel parts are produced completely on forging rolls, this equipment is often employed in conjunction with forging machines and hammers, both for preparing stock for these tools and for drawing down shanks from blocks of stock left on upset and hammer forgings.



Courtesy of Ajax Manufacturing Company

FIG. 66—FORGING ROLLS

Roll Piercing—Seamless steel tubing is made from solid round bars which are passed between two barrel-shaped rolls having their axes in different planes as illustrated in Fig. 67. Bars of the correct length and diameter to produce the size and length of tube desired are first centered at one end to a depth of about one inch, and then heated uniformly to about 2000 degrees F. With the rolls revolving at a constant speed, a bar is pushed (centered end first) into the space between the rolls. The shape and position of the rolls cause the bar to be pulled through and rotated. Furthermore, the action of the rolls draws the metal away from the center, thus starting a central cavity. The hot metal spreads over a tapered mandrel which is held in position between the rolls by a water-cooled rod. The rod is carried in a thrust bearing so that both the rod and mandrel rotate at the same speed as the bar. After the entire bar has been forced over the mandrel, the rod is withdrawn from the tube, another cold mandrel is placed on the end of the rod, and the piercing operation is repeated. In this method, known as the Mannesmann process, the mandrel serves only to enlarge the opening and to smooth the interior of the tube.

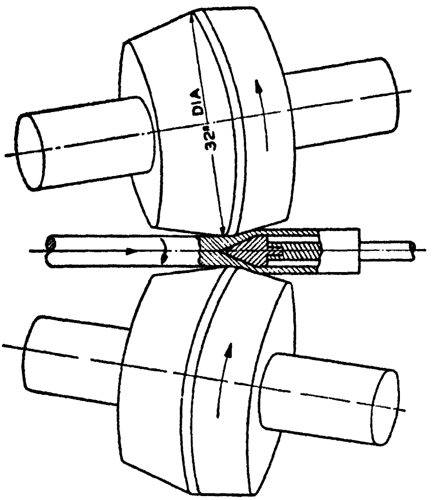


FIG. 67—ROLLS AND MANDREL USED IN PIERCING

After the piercing operation, the hollow bar is passed over a tapered plug and through grooved rolls in a two-high mill where the thickness is decreased and the length is increased. In another process, the hot-pierced bar is stripped over a long polished steel bar, and the assembly is passed through a series of grooved rolls to obtain the desired reduction. As the tube leaves the rolling mill, it is slightly oval shaped, oversize, and not perfectly smooth. It is then transferred to the reeler, which has two rolls similar to the piercing rolls, but with flat surfaces. In this mill, the tube is rolled over a mandrel on the end of a long bar, thus producing very smooth surfaces on both the inside and the outside of the tube. The next operation is to finish the tube to the exact dimensions; this is done by passing it through sets of horizontal and vertical grooved rolls, without working over a mandrel. The metal is gradually compressed until the specified outside diameter is obtained.

Rolling and Welding Pipe—Lap-welded steel pipe is made from skelp, a flat strip rolled to the desired thickness and having a width equal to the circumference of the pipe plus the lap. See Fig. 68. The edges are beveled by passing the heated skelp through rolls, so that the thickness of the wall of the finished pipe will be uniform throughout. Two furnaces are employed in this process, one called the bending furnace for heating the skelp to the temperature used in bending and the other known as the welding furnace for heating the bent skelp to the welding temperature. For all sizes less than 8 inches in diameter, the heated skelp is bent to the circular form by drawing it through a bell-mouthed die; larger sizes are formed by rolling the skelp sidewise in a set of bending rolls. The formed skelp is then heated in the welding furnace, from which it passes over a ball or mandrel and between a pair of rolls with grooves corresponding to the outside diameter of the pipe. The mandrel is held in position on a long bar over which the pipe passes as shown in Fig. 69. The rolls press the two beveled edges together, thus completing the weld. The pipe is then sized by passing through grooved rolls and is straightened between other rolls. After the pipe has been finished and inspected, it is subjected to hydrostatic pressure before being approved for service. Lap-welded pipe is made in sizes $1\frac{1}{4}$ to 26 inches in inside diameter.

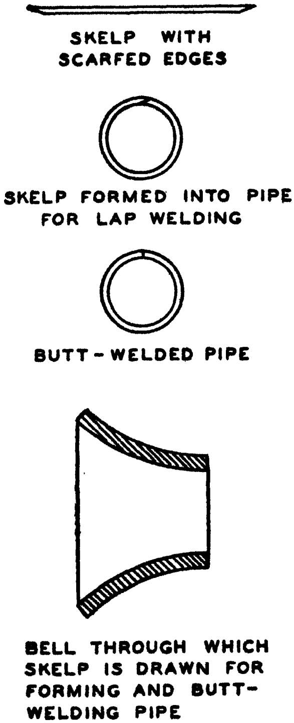

SKELP WITH SCARFED EDGES
SKELP FORMED INTO PIPE FOR LAP WELDING
BUTT-WELDED PIPE
BELL THROUGH WHICH SKELP IS DRAWN FOR FORMING AND BUTT-WELDING PIPE

Fig. 68—Welded Pipe

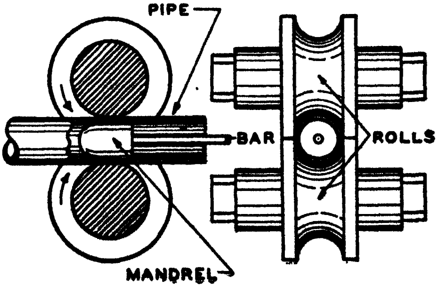


Fig. 69—Rolls for Welding Pipe

The skelp which is used to make butt-welded pipe has both edges slightly beveled so that they will meet squarely when the skelp is formed to the cylindrical shape. Before the skelp is heated, the front corners are cut off at about a 60-degree angle to assist in starting each piece through the bell or forming die. Large gas-fired furnaces are employed to heat the skelp to the welding temperature. One piece of skelp at a time is grasped by a pair of tongs and is drawn through the bell-shaped welding die. See Fig. 68. This operation curls the strip to a circular form and forces the edges together with sufficient pressure to produce a continuous weld. The pipe then passes through a series of rolls to obtain uniformity and straightness. If the pipe is to be galvanized, a coating of zinc is applied inside and outside by the hot-dip method. Each length of pipe is threaded and tested before being shipped from the mill. Butt-welded steel pipe is made in sizes $\frac{1}{8}$ to 3 inches in inside diameter. It is used extensively for gas and water lines as well as for various mechanical and structural purposes.

In the making of electrically welded pipe, pieces of steel are sheared from plates to the desired widths and lengths, after which they are passed through forming rolls where they are gradually shaped into cylindrical blanks. At the welder, the two edges of each blank are heated electrically to the welding temperature and are then forced together between rolls to complete the weld.

COLD-WORKING PROCESSES

Steel which has been formed to the final shapes by hot working is unavoidably covered with scale which causes the surfaces to be somewhat rough. Furthermore, the contraction of the steel as it cools from the finishing temperature is not constant and exact dimensions can not be obtained. To produce smooth surfaces and accurate dimensions, hot-rolled shapes are finished by cold-rolling and cold-drawing processes. Cold rolling of sheet and strip or cold drawing of wire, bars, and tubing strengthens and hardens the steel. In another cold-working process, sheets and strips are pressed between dies to obtain the desired shapes.

Cold-Rolling Process

As a preliminary step to the cold-rolling operation, sheets and strips of hot-rolled steel are immersed in an acid solution to remove the scale and then rinsed in water. The cleaned steel is passed repeatedly through sets of rolls thereby producing a slight reduction in each pass until the required thickness is obtained. The cold rolling produces smooth bright surfaces and an accurate thickness of the stock. In this process, the yield strength of the material is increased and the ductility is decreased.

Cold-Drawing Process

Wire is made in many shapes and sizes by drawing wire rod at room temperature through tapered holes in wire-drawing dies. The material from which wire is made is hot-rolled steel rod having the desired chemical composition and grain structure. The size of the rod varies from about $\frac{1}{4}$ to $\frac{3}{4}$ inch in diameter, depending upon the size of the finished wire. This material in coils several hundred feet in length is immersed in a hot acid solution to remove the scale and is then rinsed in water to remove the acid. The preparation of the steel rod for drawing depends upon the kind of wire to be made and the surface finish required. For dry drawing, the coils of rod are dipped in lime water and are then heated to dry the lime coating. A lubricant such as soap or grease is usually provided at the die to assist in the drawing operation. For wet drawing, the coils are immersed in a dilute acid solution of copper or tin sulphate, or a mixture of both depending upon the color desired. The coils are then removed and placed in a tank containing a fermented liquor made of rye meal and yeast which serves as a lubricant when the wire is being drawn.

The drawing operation is started by pointing the end of the rod and pushing it through the tapered hole in the die (see Fig. 70). The end is then gripped by tongs and sufficient wire is pulled through the die so that the wire can be attached to a power-operated reel. The reel is then rotated at a speed which will draw the wire through the die at the desired rate.

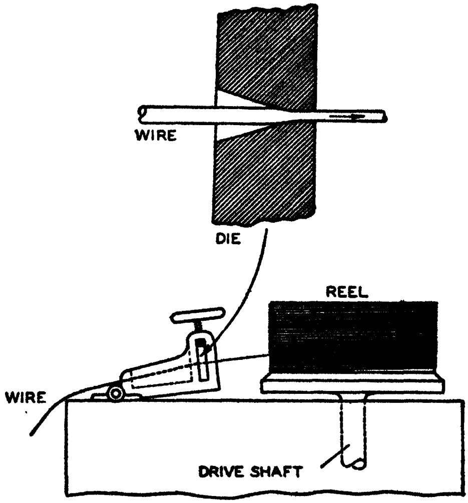


FIG. 70—WIRE-DRAWING BLOCK AND ENLARGED SECTION OF DIE

Dies are made of chilled cast iron, hardened alloy steel, cemented tungsten carbide, and diamonds. The selection of the die material depends upon the composition of the wire as well as upon the size of the wire and the finish required. The reduction in the cross section of the wire for each pass through a given die varies from 10 per cent for high-carbon steel to as much as 40 per cent for low-carbon steel. After an entire coil has been drawn through one or more dies, the operation is repeated until the desired size is obtained. In passing through the dies, the steel is severely cold worked and only a limited amount of reduction in size is possible before the wire becomes too brittle for further drawing, and must be annealed. To soften the wire, it is passed through a furnace where it is heated to a temperature in the vicinity of, or slightly lower than, the critical range. Practically any degree of hardness and strength can be obtained in finished wire by controlling the composition of the steel and the reduction in size after the annealing treatment.

Large quantities of carbon and alloy steel bars are finished by cold drawing through dies after the hot-rolled steel has been treated in an acid solution to remove the scale, and then immersed in a lime solution to neutralize the acid. In finishing regular shapes such as rounds, hexagons, squares, and flats, hot-rolled bars are used of the same shapes but sufficiently oversize to allow for the reduction during the cold-drawing operation. This decrease in size or draft varies from $\frac{1}{64}$ to $\frac{1}{8}$ inch, depending upon the composition, shape, and size of the material being drawn, and upon the physical properties desired in the finished bars. In this process, the hot-rolled bar is actually stretched through the die. For example, a bar $1\frac{1}{16}$ inches in diameter and 33 feet long will elongate about 3 feet when reduced to 1 inch in diameter. The cleaned bars are pointed at one end and are pulled through dies mounted on a machine known as a drawbench. This equipment has a heavy power-driven endless chain to which tongs are attached for pulling the bars through the dies. Some drawbenches are designed to draw one bar at a time, others as many as six at a time. The dies are made of heat-treated tool steel or cemented tungsten carbide. As a rule, the final size is obtained by one pass through the dies, although some shapes require two or more passes. After the bars are cold drawn, they are straightened in a machine having groups of rolls in pairs placed at an angle so that the bars are propelled through the machine. This operation also produces a polished surface on the bars.

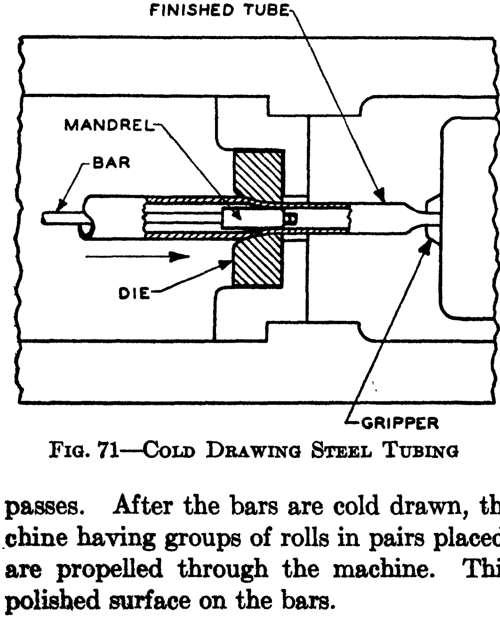
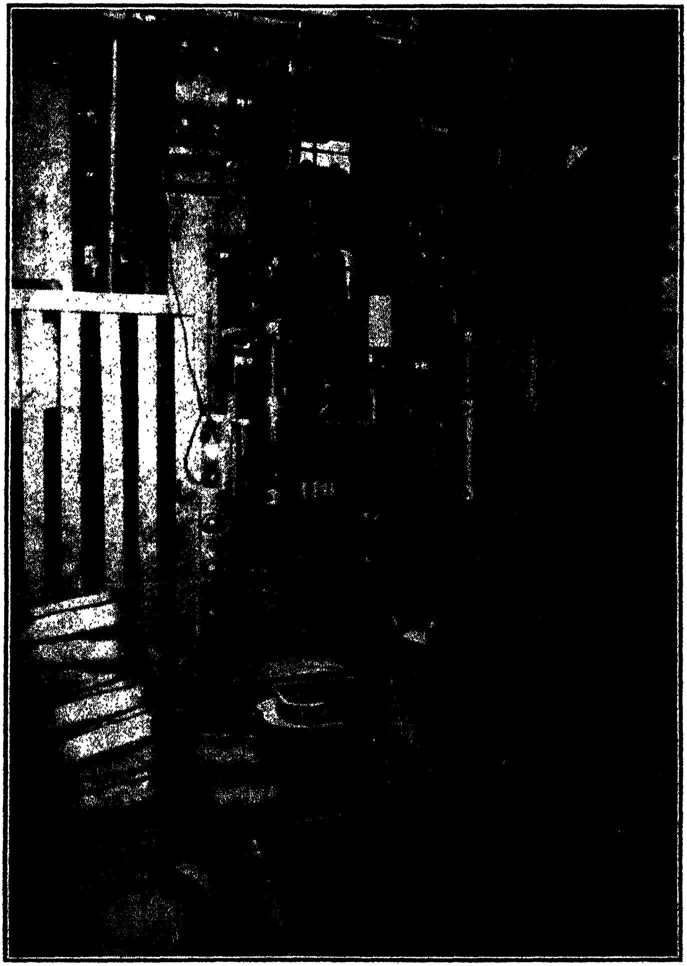


Fig. 71—Cold Drawing Steel Tubing

Seamless steel tubing is often cold finished by drawing the material through dies of the required smaller sizes. The hot-formed tubing is first pickled to remove all scale, after which it is washed and dried. It is then coated on the inside and outside with a liquid mixture of flour and tallow or other suitable lubricant. One end of the tube which has previously been pointed is inserted through the die and is gripped by the drawing tongs. At the same time, a mandrel attached to the end of a long rod is pushed in the tube at the open end all the way to the die as shown in Fig. 71. When the drawing tongs are attached to the endless chain of the drawbench and the tube is pulled through the die, the mandrel on the inside of the tube centers itself in the die opening, where it remains until the entire tube is drawn over it. One pass is sometimes sufficient to finish a tube to the required size, but usually two or more passes through dies of decreasing diameters are necessary. After each pass, the tube must be annealed, then cleaned, dried, and lubricated before the next reduction. The treatment which the tube receives after drawing depends upon its use. Boiler tubes must be full-annealed, and mechanical tubing is annealed at different temperatures to obtain prop-



Courtesy of E. W. Bliss Company

FIG. 72—PRESS FOR MAKING STEEL STAMPINGS

erties suited to the service required. After annealing, the tube is straightened, cut to length, and tested before shipment.

Cold-Pressing Process

The forming of sheet or strip steel into various shapes by forcing the metal at room temperature into impressions in dies or between one or more sets of dies in mechanical presses is known as **stamping** and the products of this process are termed **stampings.** A press for making steel stampings is shown in Fig. 72. The tools used with this equipment usually consist of a die having one or more parts fastened to the bed of the press, and one or several punches carried on the movable head. The dies are subjected to severe wear, and are made of hardened steel or cast iron. Several presses are often required to perform the successive operations necessary in the making of complicated stampings.

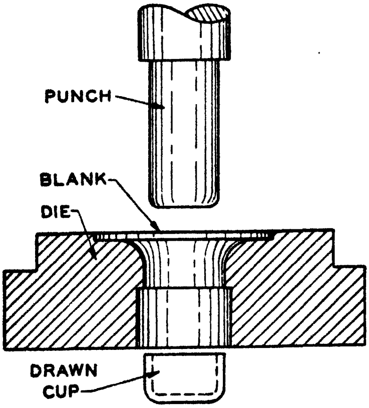


FIG. 73—DRAWING DIE AND PUNCH

In the cold-pressing process, the steel is deformed at loads beyond the yield point of the metal, hence the shape into which the metal is formed is retained after the stamping is removed from the dies. As these operations are carried on at room temperature, the steel becomes work hardened during the forming process, and the stamping must be annealed between some steps in this process when a considerable change in shape is necessary. A steel of high quality and with a low carbon content (usually less than 0.10 per cent) is required for stampings.

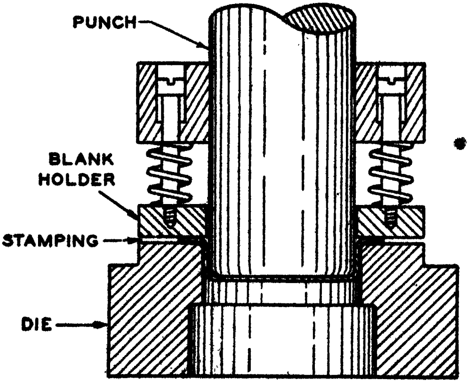


FIG. 74—DRAWING DIE WITH BLANK HOLDER

As a preliminary step to the cold-pressing operations, flat steel is often cut to suitable shapes known as blanks by shears or by blanking dies in a press. With some designs of dies, the blanking and forming operations are performed by one stroke of the press.

For making cup-shaped stampings, the design of the tools depends upon the thickness of the steel and the amount of deformation required. Blanks which are relatively thick are drawn to a cup shape with tools similar to the punch and die shown in Fig. 73. A blank is placed in the recess in the upper surface of the die, the punch is lowered, and the stamping is removed from the opening in the bottom of the die. In drawing cup-shaped parts from relatively thin stock, a blank holder is employed to prevent wrinkling while the metal is being drawn into the die. A drawing die, punch, and blank holder are shown in Fig. 74. When the punch descends, pressure is applied to the blank between the holder and the die, and the metal is gradually drawn down between the punch and the die. During the drawing operation, the blank is usually lubricated to reduce the wear on the die and to prevent scratches on the stampings.

REVIEW QUESTIONS

1. What precautions should be observed when heating steel for hot-working operations?
2. Explain the difference in construction and use of two types of steam-operated hammers.
3. State the operations which are usually required in the drop-forging process.
4. Explain the operation of a horizontal forging machine.
5. What determines the size of the grains in steel which has been hot worked?
6. Starting with steel ingots, outline the rolling practice for producing boiler plates.
7. Describe the equipment used in rolling structural sections.
8. What advantages are obtained by the cold-rolling process?
9. Describe the entire process for making steel wire in small sizes.
10. What equipment is required for making steel stampings?

CHAPTER VIII

PROCESSES USED IN HEAT TREATING STEEL

ANNEALING—**Full Annealing—Normalizing—Process Annealing—Spheroidizing** —HARDENING—**Flame Hardening—Electric Induction Heating**—TEMPERING —CASE HARDENING—**Pack Carburizing—Gas Carburizing—Heat Treatments for Carburized Parts**—CYANIDING—NITRIDING

The heat treatment of steel consists of heating and cooling operations which are carried out under controlled conditions for the purpose of obtaining certain desired properties in the steel. The improvements resulting from heat treatments are due either to the release of stresses within the steel, or to a decrease in grain size, or to the development of certain microconstituents which have the desired qualities. When steel is heated, the stresses caused by previous cold working are gradually removed from the metal. The heating of carbon steels to high temperatures brings about changes in the grain size as has been described in Chapter VI. As the properties of steel are dependent to a large extent upon its structural constituents, various degrees of strength, hardness, and ductility are obtained by the use of different heat treatments. The conditions under which the physical constituents are obtained in steel have been explained in Chapter V. When maximum softness and ductility are needed, those heat treatments which develop the largest proportion of ferrite and pearlite, or spheroidized cementite, are particularly applicable. When the most favorable combination of strength, ductility, and machinability is required in a constructional steel, a sorbitic structure is usually most satisfactory. Tool steels which require great hardness are heat treated so as to obtain a martensitic structure. Hence, the selection of the heat treatment which will produce the desired constituents will depend upon the physical requirements of each application of steel. The principal processes used in heat treating steel are annealing, hardening, tempering, case hardening, cyaniding, and nitriding.

ANNEALING

The annealing treatments involve heating the steel slowly to some predetermined temperature, holding at this temperature until the desired changes in the structure take place, and cooling slowly. The temperature to which the steel is heated and the rate of cooling depend upon the material being treated and the purpose of the treatment. The principal annealing treatments are designated as full annealing, normalizing, process annealing, and spheroidizing. The heating of steel to temperatures below the critical range after hardening, which treatment is known as tempering, may be considered a form of annealing. The discussion on tempering, however, will follow the discussion on hardening.

Full Annealing

Full annealing requires heating steel to temperatures within the full annealing range as indicated in Fig. 75, and cooling very slowly usually in the furnace, or the steel may be removed from the furnace and cooled in an insulating material which will prolong the time of cooling as compared to cooling freely in the air. The length of time for holding the steel at the annealing temperature is not less than one hour for each inch of section of the largest pieces being treated. The constituents which are present in carbon steels which have been full annealed are shown on the diagram in Fig. 37 in Chapter V. The purpose of full annealing may be to soften the steel so that it can be machined more readily, or to refine the grain structure, or to obtain physical properties between those resulting from normalizing and spheroidizing.

Steel parts having finished surfaces which must be protected from oxidation during the annealing treatment are often packed in a metal container of suitable size and shape with a layer of cast-iron borings, charcoal, lime, sand, or ground mica around the parts. The box with its contents is heated in a furnace to the correct annealing temperature and is held sufficiently long at this temperature to insure that all parts are heated uniformly throughout. At the end of this period, the box is allowed to cool in the furnace or is removed from the furnace and allowed to cool slowly to room temperature.

Normalizing

The normalizing treatment requires heating the steel to temperatures within the normalizing range (see Fig. 75) and cooling in still air at room temperature. In general, the length of time of heating is the same as for full annealing. The large grains in steels which have been cooled slowly from the molten state (as in ingots and steel castings) or have been heated to excessively high temperatures are refined when these steels are normalized. As this treatment produces a uniform structure throughout the steel, it is often used as a preliminary step for full annealing and for hardening treatments. In steels containing less than 0.83 per cent

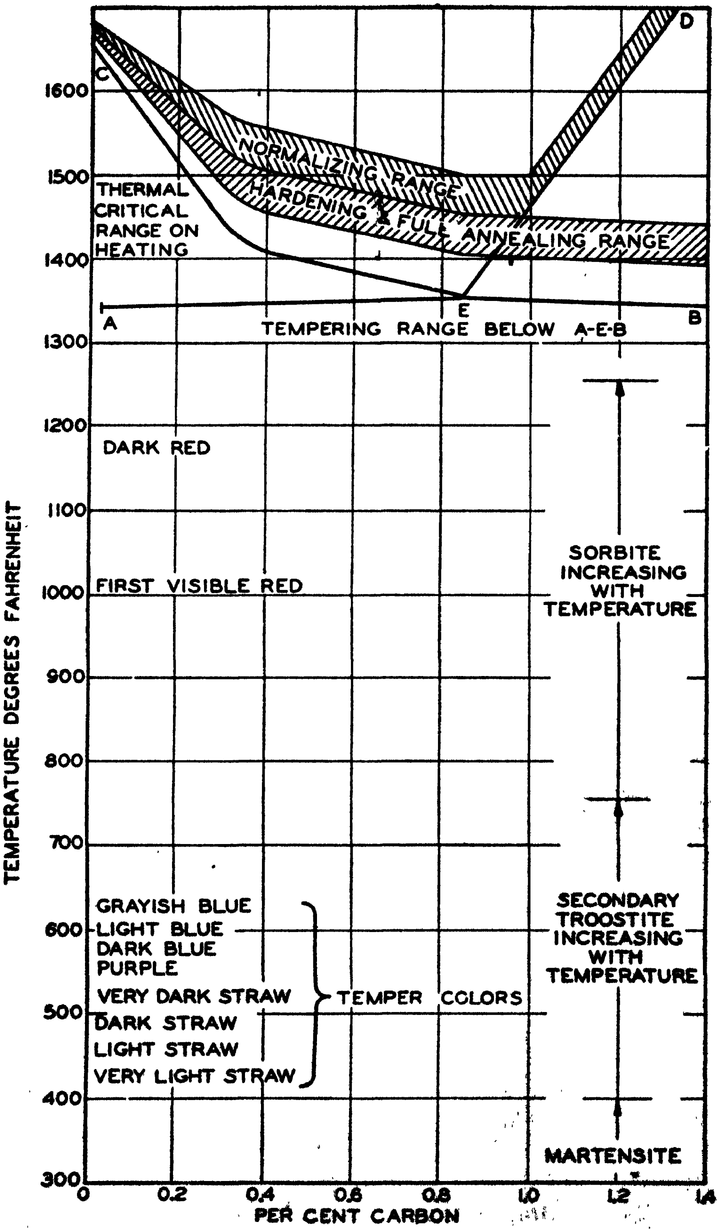


FIG. 75—TEMPERATURE RANGES USED IN HEAT TREATING CARBON STEELS

carbon, a structure composed of relatively small grains of pearlite and ferrite is ordinarily obtained when carbon steel is cooled in air after it has been heated throughout at temperatures above the critical range. The normalizing treatment is particularly advantageous for low-carbon steels which are to be machined. Normalized steel has greater strength but less ductility than the same steel after being full annealed.

Process Annealing

The treatment of steel at temperatures below or close to the lower limit of the critical range is known as process annealing. The purpose of this treatment is to increase the ductility of cold-worked steel so that it may be subjected to additional working, or so that it will be sufficiently soft for commercial uses. The cold working of steel by rolling, drawing, or forming produces internal stresses. Furthermore, the effect of cold working is to distort the normal grain structure. When the cold-worked metal is heated to a sufficiently high temperature, it is softened and a new grain structure is formed. This change in structure is known as **recrystallization**, and the lowest temperature at which it occurs in a given metal is the recrystallization temperature. This is not a fixed temperature, but varies with the extent of cold working and the length of time of heating. The greater the amount of cold working and the longer the steel is heated, the lower will be the recrystallization temperature for a given steel. The annealing of cold-worked steels for the purpose of softening them is usually done at temperatures ranging from 1020 to 1200 degrees F.

Spheroidizing

The spheroidizing treatment for high-carbon steel involves heating the steel to temperatures in the neighborhood of, but usually slightly below, the lower critical temperature on heating after the steel has been full annealed or hardened. The degree of spheroidization of the cementite depends upon the temperature of the treatment, upon the length of time the steel is held at this temperature, and upon the condition of the steel before spheroidizing. As the temperature and time for this treatment are increased, greater spheroidization or coalescence of the cementite particles takes place. If the steel is heated above the lower critical to any extent, the transformation to austenite will prevent complete formation of spheroidized cementite, and pearlite will be formed on slow cooling. Annealed pearlitic steels require longer spheroidizing treatments to produce a comparable structure than hardened steels when treated at the same temperature. After holding the steel at the spheroidizing temperature for a sufficient length of time to produce the required degree of spheroidization, the steel is usually cooled slowly.

High-carbon steels are difficult to machine unless they have received a spheroidizing treatment. Furthermore, a spheroidized structure is the most desirable condition in tool steels before they are hardened.

HARDENING

The hardening treatment for carbon steels requires heating to temperatures within the hardening range which is indicated in Fig. 75 and cooling rapidly from these temperatures, usually in water or oil. The operation of cooling rapidly is known as **quenching**. For most purposes, a structure composed largely of martensite is desired after quenching.

To obtain the most favorable conditions when hardening steels containing less than 0.83 per cent carbon, these steels are full annealed or normalized before heating for the hardening treatment. Steels containing more than 0.83 per cent carbon receive a spheroidizing treatment before hardening, so that the carbides will be present as rounded particles and not as an intergranular network.

Pieces of steel which are to be hardened should be heated uniformly throughout to the hardening temperature. The time required to produce this condition depends on the heating conditions as well as on the thickness and composition of the steel. A general rule is to allow one hour for each inch of maximum thickness when the steel is placed in a furnace which has been heated to the quenching temperature.

The hardness near the surface of carbon steels which have been quenched from temperatures above 1350 degrees F. (lower critical temperature on heating) is dependent upon: (1) the composition of the steel, particularly the carbon content; (2) the temperature from which the steel was quenched; and (3) the rate of cooling. As the maximum hardness produced on quenching varies with the carbon content as shown in Fig. 76, the hardness of quenched steel becomes greater as its carbon content is increased to about 0.70 per cent.

The temperature from which the steel is quenched has an important bearing upon the resulting hardness at the surface. Maximum hardness is obtained in carbon steels when they are quenched from temperatures within the hardening range which is indicated in Fig. 75. When steels containing less than 0.83 per cent carbon are quenched from temperatures within the critical range (above *A–E* and below *C–E* in Fig. 28 in Chapter V), some ferrite will be present in the resulting structure, hence the maximum hardness will not be obtained. On the other hand, those steels which contain pearlite and free cementite in the annealed condition are hardened to the greatest extent when they are quenched from temperatures within the critical range (above *E–B* and below *E–D* in Fig. 28). The undissolved carbides remain in the spheroidized condition after hardening, thus contributing to the hardness of the steel.

Fine-grained steels are less affected by variations in quenching temperature than coarse-grained steels because their austenitic grain size remains practically unchanged up to the temperatures ordinarily used for hardening. For this reason, fine-grained steels are preferred for most heat-treated parts.

When carbon steels are hardened by quenching, the austenite produced on heating within the hardening range must be cooled fast enough to prevent the formation of primary troostite near the surface. The minimum rate of cooling that will prevent the formation of primary troostite is known as the **critical cooling rate.** The highest hardness will be obtained when carbon and alloy steels are cooled from their hardening temperatures at rates greater than their critical cooling rates.

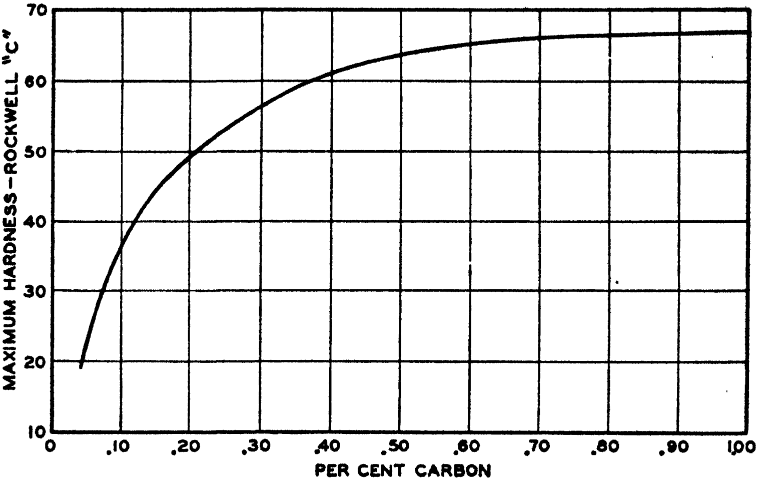
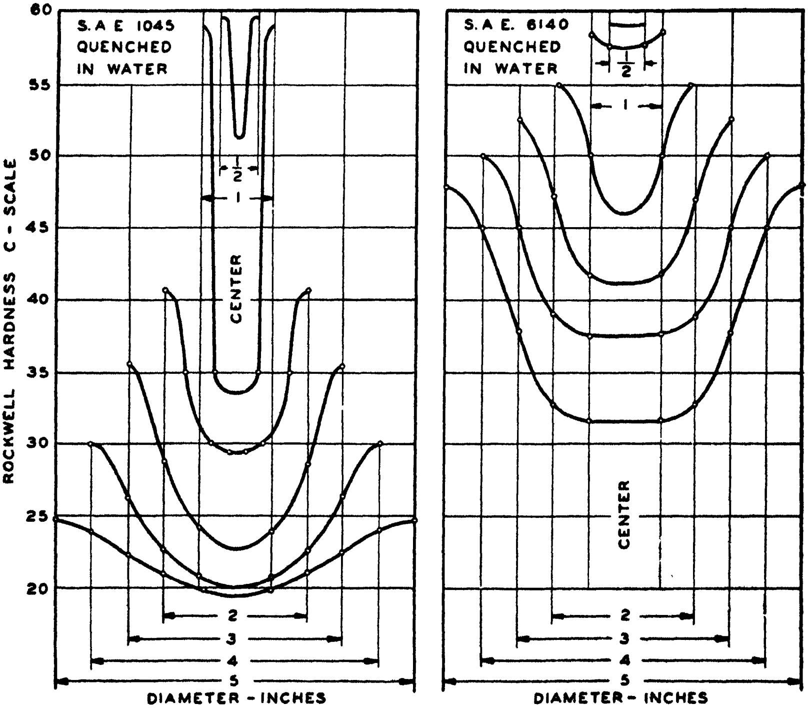


FIG. 76—RELATION OF MAXIMUM HARDNESS TO CARBON CONTENT OF PLAIN CARBON AND ALLOY STEELS

In the hardening of a specific steel, a quenching liquid is usually chosen which will produce a rate of cooling equal to or greater than the critical cooling rate for this steel. The choice of quenching liquids is influenced largely by the chemical composition of the steel. Another factor which must be considered is the intricacy of the design of the steel parts to be hardened. To avoid cracks during quenching, a less drastic quench must be used for some complicated shapes than would be necessary to produce a fully hardened structure. Those steels in which a martensitic structure is obtained on quenching in water are known as water-hardening steels. If an oil quench is sufficiently rapid to obtain martensite, the steel is described as an oil-hardening type. Air-hardening steels are those which contain sufficient alloys to be hardened when cooled from the hardening temperature in air at room temperature.

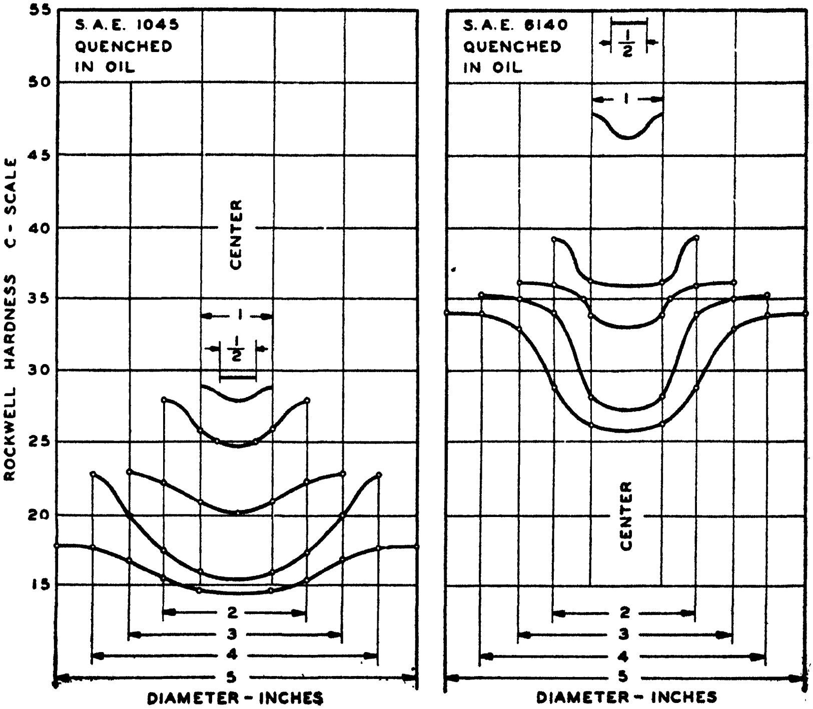
The most common quenching liquids are oil, water, and water solutions of caustic soda or ordinary salt. Solutions containing 3 to 10 per cent caustic soda (sodium hydroxide) or 5 to 15 per cent salt (sodium chloride) are more rapid in their quenching effect than water. Soft spots are less likely to be found on steel parts quenched in these solutions than when quenched in water alone. Another effect of the salts in solution is to cause the scale on the parts to be blown off during the quench. The most satisfactory results are obtained when the temperature of the



Courtesy of Carnegie-Illinois Steel Company

FIG. 77—HARDNESS VALUES FROM OUTSIDE TO CENTER OF BARS QUENCHED IN WATER

water or water solutions is not allowed to exceed 70 degrees F. Oils are less drastic than water and cause less distortion of the quenched parts. As all quenching oils must have a relatively high flash point, many of these oils are quite viscous at room temperature. When the oils are used at higher temperatures, they become more fluid, and the circulation of the oil in contact with the parts being quenched is increased. A temperature range of 90 to 140 degrees F. is usually preferred for quenching oil.



Courtesy of Carnegie-Illinois Steel Company

FIG. 78—HARDNESS VALUES FROM OUTSIDE TO CENTER OF BARS QUENCHED IN OIL

The hardening characteristics of any steel can be determined by quenching specimens of different sizes and measuring the hardness across a transverse section of each specimen. The curves in Fig. 77 show the variations in hardness from outside to center in specimens ½ to 5 inches in diameter of *S.A.E.* 1045 and *S.A.E.* 6140 steels after quenching in water from their hardening temperatures. Note that the hardness values at the surfaces of the ½-inch specimens are practically the same for the two steels. As the size increases, the hardness values at the surfaces of the specimens are progressively lower, but these values for the carbon steel decrease more rapidly than for the alloy steel. Furthermore, the hardness values of the carbon-steel specimens in the smaller sizes decrease rapidly from the outside to the center, whereas higher hardnesses are found at greater depths in corresponding alloy-steel specimens. The decrease in hardness from the outside to the center of bars of both carbon and alloy steels is caused by slower cooling rates as the centers of the bars are approached. At the surface, the heat is removed most rapidly by the quenching liquid, whereas the heat at the center must be conducted through successive layers of metal to the outside. As indicated by the curves in Fig. 77, the influence of the alloying elements in the *S.A.E.* 6140 steel was to produce higher hardness values below the surfaces of the specimens than were obtained with the carbon-steel specimens of the same size and with the same surface cooling velocity.

It was pointed out that water quenching is too drastic for some complicated designs of steel parts and that a more mild quench must be used to avoid cracks in the hardened parts. The curves in Fig. 78 indicate the hardness values throughout specimens of carbon steel (*S.A.E.* 1045) and alloy steel (*S.A.E.* 6140) after quenching in oil from their hardening temperatures. The specimens of alloy steel are much harder than those of carbon steel in equivalent sizes. When the curves in Fig. 78 are compared with those in Fig. 77, it is plainly evident that the hardness values are lower both on the outside and in the interior of specimens quenched in oil than of corresponding specimens quenched in water.

Flame Hardening

In this process, the metal at and near the surface of a steel part is brought rapidly to the hardening temperature by means of an oxy-acetylene flame, and is immediately quenched by a spray of water or by an air blast. The operations for flame hardening are carried out in several ways. Small areas may be heated by the flame in one position and quenched after the hardening temperature is reached. In the progressive method of hardening, the torch with a multi-flame tip is moved continuously over the area to be hardened, or the work is moved under the torch. Immediately behind the flame is a stream or spray of water which progressively quenches the heated zone. The speed of relative movement of the torch may vary from 4 to 10 inches per minute, depending upon the depth of hardness required, the composition of the steel, and the thickness of the material. Cylindrical surfaces are flame hardened most satisfactorily by spinning the part under the flames of one or more stationary torches, and finally quenching the heated portion while it is spinning.

The time allowed for the diffusion of the intense heat from the oxyacetylene flame is so limited that the depth to which the steel is heated above its hardening temperature is usually not more than $\frac{1}{4}$ inch. Furthermore, the external quenching of the heated portion by means of water or air is aided by the removal of heat through the base metal. This produces a harder surface than could be obtained with the conventional method of heating the entire mass of metal and then abstracting all the heat through the surface by quenching. Hardness values up to 600 Brinell are obtained on the surfaces of flame-hardened *S.A.E.* 1045 steel.

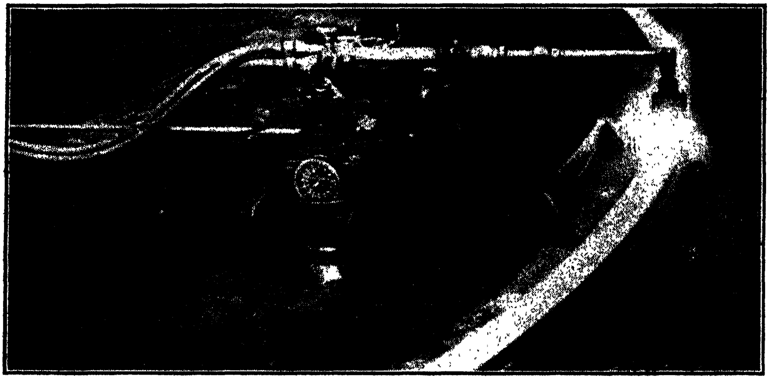
Any steel which will respond to a heating and quenching treatment can be flame hardened. In plain carbon steels, the carbon content should be at least 0.35 per cent, and preferably 0.40 to 0.70 per cent. Steels with a higher carbon content can be flame hardened, but difficulties arise from surface checking and cracking. Furthermore, alloy steels, particularly those with a low alloy content and with the carbon not less than 0.35 per cent, are well suited to flame hardening.

Courtesy of Gleason Works

FIG. 79—EQUIPMENT FOR FLAME HARDENING GEAR TEETH

The advantage of flame hardening over furnace heating and quenching lies in the possibility of hardening relatively small areas on large machine parts without causing distortion and without changing the structure of other portions. Large gears and pinions which are difficult to heat treat by other methods are flame hardened only on the wearing surfaces of the teeth. Equipment for flame hardening the teeth of gears is illustrated in Fig. 79. The operation of this machine, other than indexing, is entirely mechanical. Both sides of a tooth are hardened at the same time, thus avoiding distortion of the teeth. High hardness values are obtained without changing the chemical composition of the steel and without oxidizing the surfaces.

Flame hardening is the most satisfactory method for hardening the bearing areas of large shafts and other machine parts. The equipment shown in Fig. 80 was used for hardening a roller path on a cast-steel ring 14 feet in diameter. The torch is carried on a tractor which is guided in a circle by a radius rod. The speed of the motor-driven tractor can be adjusted to meet any requirements. In the head of the torch, a sufficient number of tips are provided to span the area to be hardened. The quenching water passes through the head of the torch and issues in a number of streams directly back of the flame. About 4 square inches of surface can be hardened with 1 cubic foot each of oxygen and acetylene.



Courtesy of Air Reduction Sales Company

FIG. 80—EQUIPMENT FOR FLAME HARDENING SURFACE ON CAST-STEEL RING

Diameter of ring 14 feet.
Width of hardened path 2¾ inches.
Travel of torch 5 inches per minute.
Final hardness of steel 375 to 415 B.H.N.

Electric Induction Heating

The bearing areas on crankshafts and other steel parts are heated for hardening by passing an alternating current of 2,000 cycles through copper inductor blocks which surround but do not touch the surfaces to be hardened. This high-frequency current induces a high current in the steel which causes the metal to be heated to the quenching temperature for a depth of approximately $\frac{1}{8}$ inch in about 5 seconds. The heated areas are then quenched immediately by sprays of water delivered through holes in the inductor blocks. Suitable electrical devices are provided to control the intensity of the induced current, and the time of heating so that uniform results are obtained regularly with this method of hardening. A preliminary heat treatment produces the desired toughness in the steel, and, after the localized hardening treatment, the parts are tempered at about 350 degrees F.

TEMPERING

The tempering treatment requires the reheating of steels after hardening to temperatures below the critical range, followed by any desired rate of cooling. Steels which have been quenched from the hardening temperatures are in a stressed condition, and those with a high carbon content are very low in ductility. To remove the quenching stresses and to increase the ductility, these steels are reheated to lower temperatures immediately after hardening. The tempering range for carbon-steel tools is usually from 300 to 600 degrees F., depending upon the service required of the tools. As the tempering temperature is raised, the hardness of the steel is decreased, but the resistance to shock is increased.

TABLE IX

PROPERTIES OF *S.A.E.* 1045 STEEL AFTER HEAT TREATING

Heat Treatment for Specimens ¾ In. in Diameter	Yield Point, Pounds per Square Inch	Tensile Strength, Pounds per Square Inch	Elongation, Per Cent in 2 Inches	Reduction of Area, Per Cent
Furnace cooled from 1500° F....	49,325	89,175	26.5	47.0
Quenched in water from 1500° F. tempered at 800° F..........	142,850	160,650	14.0	44.0
Quenched in water from 1500° F. tempered at 900° F..........	121,650	141,075	17.5	53.0
Quenched in water from 1500° F. tempered at 1000° F.........	107,350	127,450	20.0	56.5
Quenched in water from 1500° F. tempered at 1100° F.........	100,750	115,900	24.0	63.0
Quenched in water from 1500° F. tempered at 1200° F.........	87,100	104,450	27.5	66.0
Quenched in water from 1500° F. tempered at 1300° F.........	76,300	93,850	30.0	69.0

Constructional steels are usually tempered above 600 degrees F. to obtain the necessary ductility. The test data given in Table IX show the effects of different tempering temperatures on the properties of a carbon steel. As the reheating temperature is increased, the yield point and tensile strength are lowered, but the elongation and reduction of area become greater.

The characteristic changes in the physical constitution of steel as the result of tempering are the formation of secondary troostite from martensite in tool steels, and the development of sorbite from martensite in constructional steels. These changes in the constituents take place gradually. The higher the tempering temperature, the further the change progresses from the martensitic structure of hardened steel toward the softer spheroidized structure. If the purpose for which the steel is to be used requires extreme hardness, it is tempered at temperatures below 400 degrees F. only to relieve internal stresses. When hardness as well as some resistance to shock are needed, the steel is tempered so as to obtain some secondary troostite. If strength and ductility are required for parts which are to be machined, a sorbitic structure is produced by tempering.

In the heat treatment of tools, the degree of tempering is sometimes judged by the color of the film of oxide formed on the surfaces of the polished steel while it is being heated in the air. This color is an indication of the tempered condition of the steel and is dependent upon the length of time and the temperature of heating. In Table X the temperatures corresponding to different oxide colors are given with the names of the tools which are usually tempered at these temperatures. Lathe tools made of carbon steel containing 1.10 per cent carbon after quenching in water from 1450 degrees F. have a structure composed of martensite and cementite. When these tools (see Fig. 126 in the Appendix) are tempered on the cutting edge to a light straw color (450

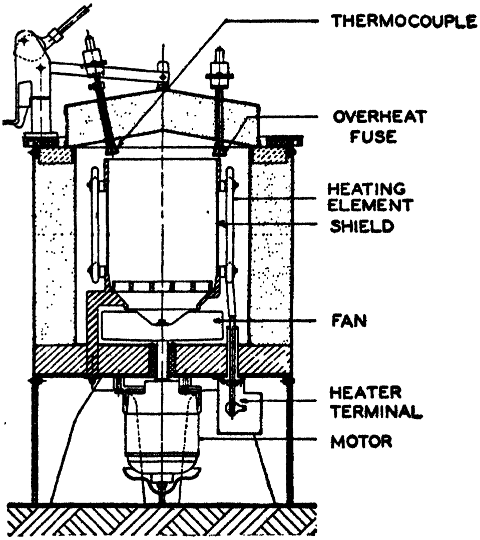
TABLE X

TEMPERING CHART

Carbon Steel Tools	Oxide Color	Temperature, Degrees F. for 5 Minutes
Lathe tools, milling cutters, twist drills	Light straw	450
Flat drills, taps, dies, wood-cutting tools	Dark straw	490
Cold chisels, bending dies, shear blades	Purple	550
Screw drivers, tools for hot work	Light blue	600

degrees F.), a small proportion of the martensite is changed to secondary troostite, but most of the structure is composed of the harder constituents. On the other hand, cold chisels made of carbon steel with 0.83 per cent carbon (see Fig. 125 in the Appendix) are tempered to a purple color (550 degrees F.) so that a greater proportion of the hard martensite produced after quenching will be changed to secondary troostite with an improvement in resistance to impact.

Steel parts are often tempered in electrically heated or gas-fired furnaces within which the air is circulated to produce uniform temperatures. See Fig. 81, and Fig. 88 in Chapter IX. A bath of oil is satisfactory for tempering some carbon-steel tools. When required temperatures are higher than 500 degrees F., molten lead or fused salts may be used in bath furnaces for heating the steel. To avoid the development of cracks in tools of irregular shape, tempering is performed immediately after hardening and before the steel has cooled to room temperature.



Courtesy of Leeds and Northrup Company

FIG. 81—CROSS SECTION OF TEMPERING FURNACE

Cover, walls, and bottom are insulated. Work is placed in the furnace after the cover is raised and turned to one side. Air is circulated by a motor-driven fan up past the electric heating elements and down through the work.

CASE HARDENING

Machine parts such as gears, piston pins, and rollers which require hard, wear-resisting surfaces as well as shock-resisting properties are generally case hardened. In this process, a layer or case of high-carbon steel is produced on parts made of low-carbon steel. The composite steel is heat treated to develop the desired properties in the case as well as in the interior portion known as the core. The carbon content of the metal at the surface is increased by heating the low-carbon steel to temperatures above the critical range in the presence of carbonaceous gases. This is accomplished either by the pack-carburizing process or by the gas-carburizing process.

Pack Carburizing

In the pack-carburizing process, the parts to be case hardened are packed in a metal container with carburizing compound and are heated in a furnace to temperatures within the austenitic range. The amount of carbon absorbed by the steel during carburizing is dependent upon: (1) the initial composition of the steel, (2) the temperature at which the steel is heated, (3) the length of time the steel is held at the carburizing temperature, and (4) the nature of the carburizing material. The lower the carbon content of the steel, the more readily will carbon be absorbed. Furthermore, low-carbon steels can be readily machined before being case hardened. As a tough core is usually desired for case-hardened parts, steels containing between 0.10 and 0.30 per cent carbon with or without alloys are ordinarily used for this purpose. The following steels are commonly selected for case-hardened parts: *S.A.E.* 1015, *S.A.E.* 1020, *S.A.E.* 1025, *S.A.E.* 2515, *S.A.E.* 3115, *S.A.E.* 4120, *S.A.E.* 4620, and *S.A.E.* 6120. A fine-grain steel is often preferred because of the simplified heat treatment which may be used after carburizing.

The carburizing compound contains a mixture of wood charcoal, bone charcoal, and coke. Bone charcoal sustains the carburizing action of the compound longer than the wood charcoal and shrinks less at the carburizing temperatures, so the two materials are often used together. Coke acts as a filler and reduces the shrinkage that takes place during carburizing. When these carbonaceous materials are heated to carburizing temperatures, they combine with the oxygen in the carburizing box to form carbon monoxide. The carbon monoxide in contact with the surface of the steel at high temperatures decomposes to carbon which is absorbed by the steel and gradually diffuses inward.

Materials known as energizers are commonly added to carburizing compounds to increase the concentration of carbon monoxide and thus improve the rate of carburizing. The most effective energizers are barium carbonate and sodium carbonate. A typical carburizing compound contains 60 per cent charcoal, 25 per cent coke, 14 per cent barium carbonate, and 1 per cent sodium carbonate. The amount of sodium carbonate is kept low because its gaseous decomposition products attack the carburizing boxes.

When only certain areas of steel parts are to be case hardened, those surfaces which are to remain soft may be electroplated with copper. The procedure commonly used is to copper plate the entire object and then to remove the copper from those surfaces which are to be carburized. Drilled and tapped holes may be plugged with a fire clay cement to prevent the carburizing gases from coming in contact with surfaces which are to remain soft. Another procedure is to provide extra metal on portions which must not harden after heat treating and to machine off the carburized metal from these portions after the parts have been cooled in the boxes.

When solid carburizers are used, the parts to be carburized are packed in metal containers of suitable size and shape so that at least ½ inch of the carburizing compound surrounds each piece of steel. The containers are made of cast steel, pressed steel, or any one of a number of heat-resisting alloys. As uniform heating of the parts is desirable, the containers should be relatively narrow so that the difference in temperature within the box will not be too great. In packing the boxes, the parts should be arranged so that the least amount of deformation or sagging occurs during carburizing because the metal becomes softened at the carburizing temperatures.

After the carburizing boxes or pots are properly packed, they are placed in furnaces where they are heated to temperatures considerably above the critical range. As the temperature to which the steel is heated for carburizing increases, the rate at which carbon is absorbed becomes greater. There are, however, several factors

FIG. 82—MICROSTRUCTURE OF CARBURIZED STEEL

Courtesy of R. L. Dowdell

which limit the temperatures for carburizing. The cost of maintaining furnace linings become excessive when very high temperatures are used. Also, the grain size of the steel increases at very high temperatures, and it is difficult to refine large grains in the subsequent heat treatment. The carburizing temperatures are usually 1650 to 1750 degrees F.

The amount of carbon diffused into the steel and the depth of the case increase with the length of time at the carburizing temperature. Under average conditions, a case of high-carbon steel $\frac{1}{32}$ inch deep will be produced in 5 hours at 1700 degrees F. The total heating time will include the length of time necessary to heat the boxes and contents to the carburizing temperature. The depth of case ordinarily required is $\frac{1}{32}$ (0.031) inch to $\frac{1}{16}$ (0.063) inch, although cases of greater thickness can be obtained. Case-hardened parts are often ground to accurate dimensions after heat treating, and the case depth must be sufficient to provide for the amount removed in grinding, in addition to the required final thickness of the case. The carbon content of carburized parts decreases from about 1.10 per cent at the surface to the original carbon content of the steel in the core. This carbon drop or carbon gradient should be a gradual decrease for the total depth of the case to prevent spalling or breaking off of the case. The microstructure near the surface of a piece of *S.A.E.* 1020 steel which was cooled slowly after carburizing is shown in Fig. 82. The structure in the upper part of the illustration (nearest the surface) is composed of pearlite with cementite at the grain boundaries. Farther from the surface only pearlite is present, and at greater depth the constituents are ferrite and pearlite.

Gas Carburizing

A high-carbon case can be produced on parts made of low-carbon steel by heating them to temperatures above the critical range in gases rich in carbon. In this process, the parts are exposed to carbonaceous gases that are admitted to the retort or muffle within the furnace. Continuous or intermittent operations may be used depending on the furnace equipment. In the batch process, the parts to be carburized are held in a wire basket which is suspended in a gas-tight retort or the parts are tumbled in a rotary retort, each heated to the carburizing temperature. Greater economy and output can be obtained in continuous gas carburizing furnaces which are usually of the muffle type. The parts are put on trays and are pushed through the muffle at a rate which will permit the desired depth of case to be produced during the carburizing period. The muffles used for this purpose are made in several sections of heat-resisting alloys. To permit continuous passage of the trays without allowing the carburizing gas to escape, the muffles are closed at each end by two doors, one of which is always kept closed during the operation of the furnace.

Natural gas, which contains a large amount of methane (CH_4), may be used for a carburizing atmosphere or this gas may be diluted with flue gas of constant composition or with a small amount of air to produce a case of a more uniform carbon gradient in continuous operation. Heavier hydrocarbon gases or liquids may also be employed for carburizing purposes. At the carburizing temperatures, these hydrocarbons are dissociated to form methane and other decomposition products. The temperatures for gas carburizing are usually 1600 to 1750 degrees F. In this process, an average case depth of 0.045 inch is obtained in a total time of 6 hours.

Heat Treatments for Carburized Parts

On completion of the carburizing treatment, the composite steel, having a high-carbon case and a low-carbon core, is heat treated in different ways depending on the results desired. The three principal heat treatments for carburized parts are: (1) quenching directly from the box at the carburizing temperature and tempering; (2) cooling in the box, reheating once to the desired temperature, quenching, and tempering; (3) cooling in the box, reheating twice to the desired temperatures, each followed by quenching, and finally tempering.

When a fine-grained steel is used, which does not coarsen noticeably at carburizing temperatures, the parts may be removed from the box or furnace at the carburizing temperature and quenched directly in oil or water. With this treatment, the carburizing temperature usually does not exceed 1650 degrees F. Less distortion occurs with the single direct quench than with any other hardening treatment. To relieve the stresses caused by quenching, steel parts are usually tempered at low temperatures (250 to 350 degrees F.) after the quenching operation.

Carburized parts made of steels which coarsen at the carburizing temperature are usually allowed to cool in the boxes and are heat treated later to develop the desired properties. When wear is of chief importance, these parts are heated within the hardening range of the steel in the case and are then quenched in oil or water, depending on the composition of the steel. Alloy steels are usually quenched in oil, and carbon steels in water. This treatment will produce a hard fine-grained case, but the core structure will not be refined. If the parts are heated within the hardening range of the steel in the core before quenching, both the case and the core will be hardened. The core will then be refined, but the case will have a coarse structure. After the quench, the parts are tempered at 350 degrees F. to relieve stresses.

When a fine grain structure is required throughout both the case and and the core of parts which have cooled in the boxes from the carburizing temperature, a treatment is required using a double quench. First, the parts are heated within the hardening range of the steel in the core, after which they are quenched in oil. Next, they are heated within the hardening range of the steel in the case and are quenched in oil or water. To remove stresses resulting from quenching, the parts are finally heated throughout to about 350 degrees F. The first reheat and quench produce fine grains and high physical properties in the core, whereas the second reheat and quench produce small grains and develop high hardness in the case.

CYANIDING

A process for producing hard surfaces on low-carbon or medium-carbon steels consists of immersing the steel in a molten salt bath containing sodium cyanide, and then quenching the steel in water. The high hardness obtained after this treatment is caused by the presence of compounds of nitrogen as well as of carbon in the surface layer. This is a rapid and economical method for obtaining hard surfaces on steel parts such as wrenches and gages which are subjected to a limited amount of wear.

A bath containing one-third each of sodium chloride, sodium carbonate, and sodium cyanide is used for the cyaniding treatment. This concentration of cyanide is maintained by frequent additions of sodium cyanide to the bath. The reactions which occur in the bath are indicated in the following equations: First, the sodium cyanide combines with oxygen from the air above the bath to produce sodium cyanate,

$$2NaCN + O_2 \rightarrow 2NaCNO$$

then the sodium cyanate is decomposed by the heat in the bath with the liberation of carbon monoxide and nitrogen,

$$4NaCNO + \text{heat} \rightarrow 2NaCN + Na_2CO_3 + CO + N_2$$

and finally the carbon monoxide in contact with the surface of the steel decomposes to carbon, which is absorbed by the steel along with the nitrogen to form carbides and nitrides. With the bath maintained at 1550 degrees F., a depth of case of 0.005 inch will be produced in about 15 minutes after the work reaches the temperature of the bath.

The equipment shown in Fig. 91 in Chapter IX is suitable for cyaniding small steel parts. The containers are usually made of pressed steel, although special nickel-chromium alloys have been developed for this purpose. Small parts are held in wire baskets while being heated in the cyanide bath and during quenching. All objects immersed in the bath must be free from moisture to avoid spattering of the liquid salts. Goggles and gloves should be worn by the operator to prevent burns from the cyanide. The fumes given off from the cyanide bath, because of their obnoxious character, are removed from the furnace through an exhaust system.

NITRIDING

In the nitriding process, a hard surface layer is produced on steel of special composition in an atmosphere of ammonia gas at temperatures of 900 to 1000 degrees F. The ammonia is dissociated, and the nascent nitrogen combines with the elements in the steel to form nitrides which impart extreme hardness to the surface. Special alloy steels containing approximately 1 per cent aluminum in combination with chromium or molybdenum have been developed for use in the nitriding process. These steels usually receive a preliminary heat treatment to produce a sorbitic structure which is most satisfactory for machining as well as for nitriding. To avoid chipping of the hardened case, all decarburized metal must be removed from the parts before nitriding. Surfaces which are to be protected against nitriding are coated with a layer of tin or solder.

The equipment required for nitriding consists of a suitable furnace having some means for accurate temperature control, a gas-tight container or retort made of copper-nickel alloy which will not be affected by ammonia gas at the nitriding temperature, a tank of ammonia provided with a suitable needle valve for controlling the flow of the gas, and finally a special pipette for determining the extent of the ammonia dissociation. The parts to be nitrided are placed in the retort, which is sealed and then heated in the furnace to about 950 degrees F. Ammonia gas is fed into the retort at a rate which will produce the desired concentration of active gas. Some of the gaseous products are discharged from the retort. At the end of the heating period, the parts are allowed to cool in the retort and no further treatment is required. The temperature used in this process is so low that no appreciable warping or distortion of the parts takes place, provided all stresses produced in the preliminary heat-treating and machining operations were removed. A hard surface layer about 0.015 inch in depth is produced in 50 hours. In addition to its high hardness (in excess of 1000 Brinell), the nitrided case is somewhat resistant to atmospheric corrosion. Another advantage of nitriding is that the hardness of the case is retained at temperatures up to 900 degrees F. Some of the applications of nitrided steel include gears, wrist pins, rollers, dies, and gages.

REVIEW QUESTIONS

1. What are the purposes for full annealing steel?
2. What condition in the steel is obtained by normalizing?
3. Explain the factors which affect the hardness of carbon steels which have been quenched from temperatures above 1350 degrees F.
4. Explain the critical cooling rate for steel.
5. What factors influence the depth of hardening of quenched steels?
6. Discuss the advantages of flame hardening steel.
7. Define tempering and state the ranges of temperature used in tempering tool steels and constructional steels.
8. What means are used to prevent certain areas from absorbing carbon during the carburizing treatment?
9. Outline the heat treatment which will produce a fine grain structure throughout both the case and the core of steel parts which are to be case hardened.
10. Discuss the advantages of the nitriding method for hardening the surfaces of steel parts.

CHAPTER IX

EQUIPMENT USED IN HEAT TREATING STEEL

FURNACES—**Hearth Furnaces**—Stationary-Hearth Furnaces—Movable-Hearth Furnaces—**Furnace Atmospheres**—**Bath Furnaces**—Molten Lead Bath—Molten Salt Bath—Oil Bath—QUENCHING EQUIPMENT—EQUIPMENT FOR MEASURING TEMPERATURES—**Thermoelectric Pyrometer**—**Mercury Thermometer**

Having considered the principles and the practice relating to the heat treatment of steel, it is well to give some attention to the equipment used in these processes. The apparatus required for heat treating includes furnaces within which the metal can be heated to any desired temperature, some equipment in which the temperature of the metal can be reduced from one point to another at any desired rate, and some means for measuring temperatures.

FURNACES

Furnaces which are used for heat treating steel are classified into two general groups known as hearth furnaces and bath furnaces. In hearth furnaces the steel is heated in a gaseous atmosphere; in bath furnaces the work is immersed in a liquid medium. Several different types of each of these classes of furnaces will be described later.

Another basis for the classification of furnaces is the kind of fuel used. Both large and small heat-treating furnaces are fired with oil or gas. The burners for these fuels are arranged so that the material within the furnace can be heated uniformly throughout. Electric power is also used as a source of heat for furnaces both in the tool-room size and in some larger units.

Hearth Furnaces

Hearth furnaces for oil or gas fuels are built with the heating chamber and combustion space arranged in three ways as shown in Fig. 83. First, in the **open-chamber furnace**, the metal is heated in direct contact with the products of combustion from the fuel. This type of construction is used in furnaces for annealing steel castings and for heating steel which is to be forged. Second, the **semi-muffle type**, in which combustion takes place beneath the floor of the heating chamber, is used extensively in heat-treating practice. Third, in the **muffle furnace** the hot gases surround the heating chamber but do not enter it. This type of furnace is used principally in tool rooms for the heat treatment of dies and special tools.

Many different designs of hearth furnaces are used for heat-treating purposes. In some types of construction, the hearth forms an integral part of the furnace. Other designs provide for a movable hearth to assist in handling the material into and out of the furnace.

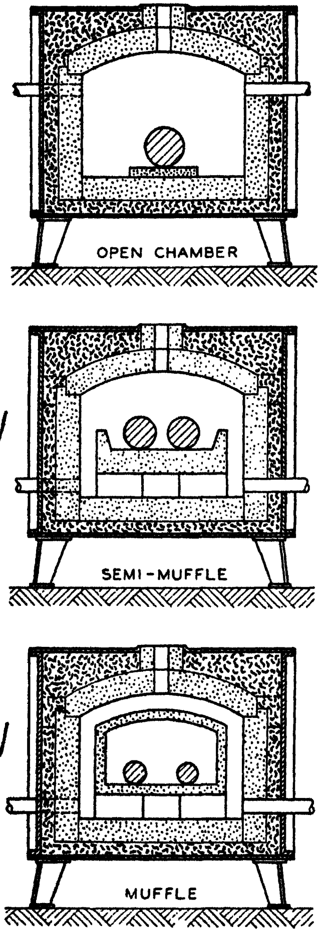
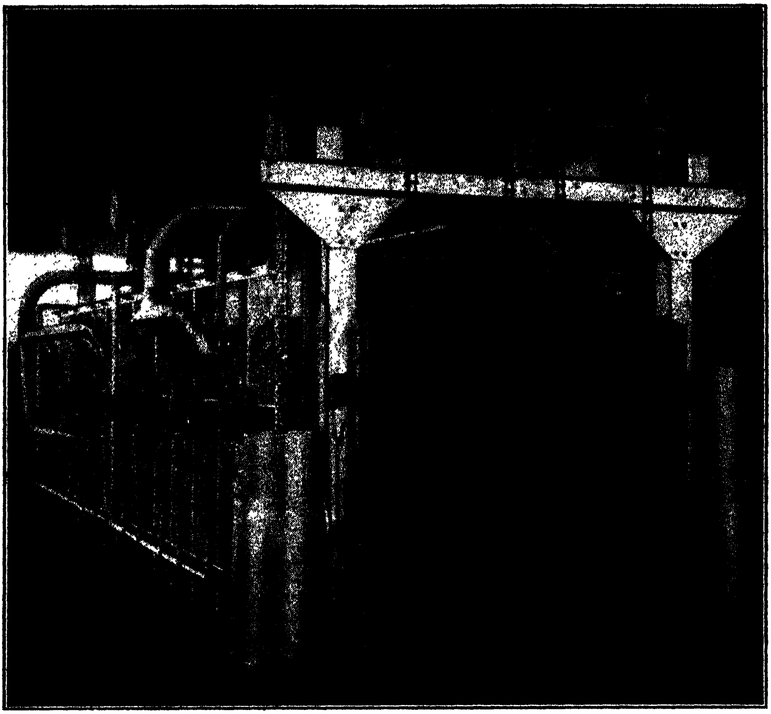


FIG. 83—CONSTRUCTION OF STATIONARY-HEARTH FURNACES

Stationary-Hearth Furnaces—The simplest type of heat-treating furnace consists of a rectangular structure of steel lined with fire brick. One end of this structure is provided with a movable door which is also lined with fire brick. This construction is known as a **box-type** or **batch-type furnace.** Small furnaces of this type are used in tool rooms for the heat treatment of miscellaneous tools. Large units are employed for heating large quantities of steel in the different heat-treating processes. See Fig. 84.

When large numbers of heat-treated parts of about the same size are required, mechanical equipment is used for transporting the work through stationary-hearth furnaces. Many forms of conveyors such as rollers, chains, and trays are employed for this purpose.✓ A furnace equipped with a chain conveyor is shown in Fig. 85. The chains which travel through the furnace are made of heat-resisting alloy steel. In the pusher-type furnace illustrated in Fig. 86, the material to be heat treated is moved forward through the furnace on alloy steel rails. Burners are provided at a number of positions both above and below the hearth.

Cover furnaces are built with the top and sides as one unit which can be lifted from the base on which the charge is placed. The cylin-



Courtesy of Mahr Manufacturing Company

FIG. 84—STATIONARY-HEARTH BATCH-TYPE FURNACE

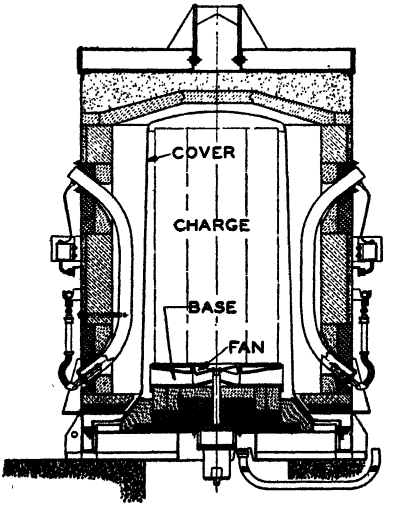
Courtesy of Surface Combustion Corporation

FIG. 85—CHAIN-CONVEYOR FURNACE

Courtesy of Surface Combustion Corporation

FIG. 86—PUSHER-TYPE FURNACE

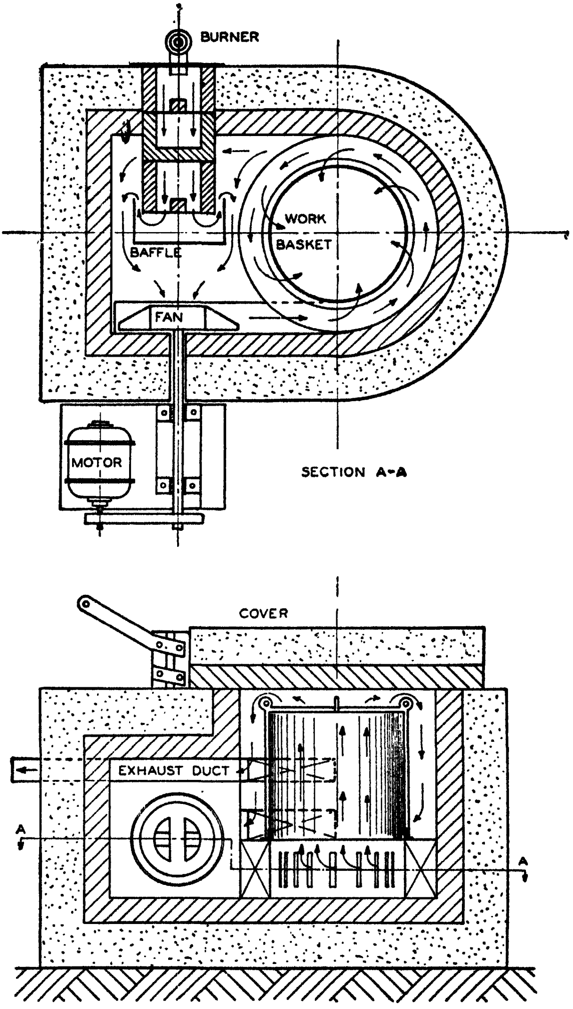
drical cover furnace shown in Fig. 87 is used for annealing coils of strip steel. These furnaces are also adapted to other heating operations. One cover unit may be used alternately with several bases, the extra bases being loaded or unloaded while one charge is being heated in the assembled furnace. Cover furnaces are heated by gas or electricity. In the furnace illustrated, gas is burned in the combustion tubes which radiate heat to the inner cover. The atmosphere in the heating chamber is circulated through the charge by the fan in the base.



Courtesy Lee Wilson Engineering Company

FIG. 87—COVER FURNACE

Recirculation or **forced convection furnaces** are equipped with fans which continually circulate the hot gases at a high velocity through the heating chamber. The gases may be heated by electric resistors as shown in the furnace in Fig. 81 in Chapter VIII, or by the combustion of gas as provided in the furnace shown in Fig. 88. In this furnace, air is heated by a gas burner and is delivered by a fan up through a basket containing the work and down around the outside of the basket. Some of the gases are exhausted and the remaining gases are mixed with the hot products of combustion from the heater for recirculation through the work. The recirculation method permits rapid uniform heating with low heat losses. This method is particularly advantageous for tempering large quantities of small parts such as lock washers, bolts, and wrenches. The parts are usually transferred to and from the furnace in metal baskets. As a rule, the maximum temperature recommended in forced convection furnaces is about 1250 degrees F.



Courtesy of Despatch Oven Company

Fig. 88—Cross Sections of Recirculation or Forced Convection Furnace

Movable-Hearth Furnaces—The charging and discharging of a large heat-treating furnace can be accomplished most conveniently by mounting the hearth on a car which can be moved from the furnace for loading or unloading. This equipment is illustrated in Fig. 89. The car-type furnace is designed for oil or gas fuel, or for electric heaters.

In some heat-treating furnaces, the work is carried through the heating chamber on a rotating hearth. A furnace with this construction is shown in Fig. 90. One or more doors are provided in the side wall for introducing and discharging the steel parts. The speed at which the hearth is rotated is adjusted so that the desired temperature is obtained in the product. The rotary-hearth furnace is used for hardening, tempering, and carburizing operations.

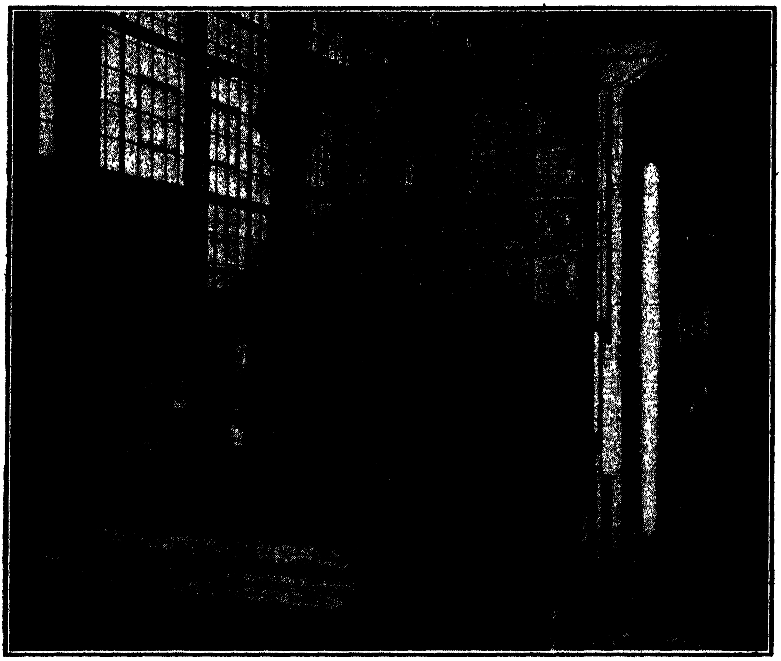
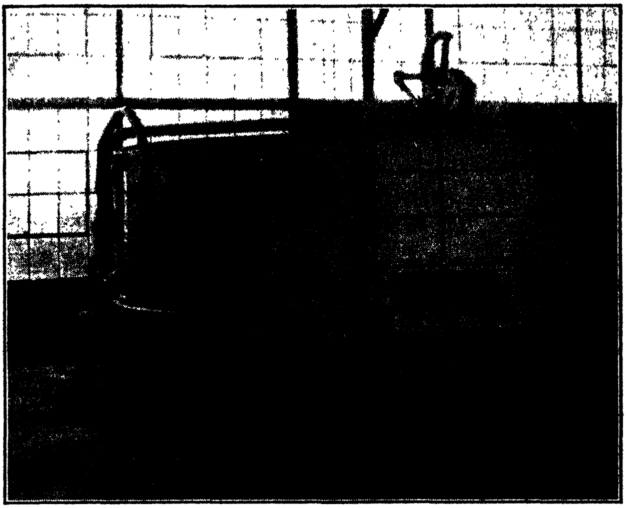


FIG. 89—CAR-TYPE FURNACE

Furnace Atmospheres

Steel which is heated to annealing, hardening, or normalizing temperatures in an open-chamber or semi-muffle furnace is necessarily exposed to the products of combustion of the fuel. The principal constituents of combustion gas are carbon dioxide (CO_2), nitrogen (N_2), water vapor (H_2O), and oxygen (O_2). Under some combustion conditions, carbon monoxide (CO) and hydrogen (H_2) may be present. The proportions of these gases in the furnace atmosphere depend upon the degree of mixing and the relative quantities of fuel and air introduced through the burners. An oxidizing or scaling atmosphere contains excess oxygen, water vapor, and carbon dioxide; whereas a reducing atmosphere contains carbon monoxide, hydrogen, and unburned hydrocarbon gases from the fuel. With certain mixtures of air and fuel, an atmosphere containing neither excess oxygen nor carbon monoxide can be obtained, but this is still a scaling atmosphere when carbon dioxide and water vapor are present. When the combustion is such that hydrogen and water vapor are present, the steel becomes decarburized (carbon is removed from the surface) at high temperatures. It is not possible to obtain a truly neutral or inactive atmosphere in the fuel-fired open-chamber or semi-muffle furnace. The most favorable combustion conditions depend upon the composition of the steel being treated and the temperatures. A slightly reducing atmosphere with about 2 per cent carbon monoxide at 1700 degrees F. produces a very light scale on carbon steels. To avoid decarburization, however, an oxidizing furnace atmosphere with excess air is usually employed; this is judged by the appearance of the flame at the exhaust flue.



Courtesy of Mahr Manufacturing Company

FIG. 90—FURNACE WITH ROTARY HEARTH

When steel is heated in a muffle furnace or in an enclosed retort, a protective atmosphere may be provided which will prevent both oxidation and decarburization of the steel. For this purpose, pure dry nitrogen, or nitrogen and hydrogen resulting from the dissociation of ammonia gas, or combinations of gases resulting from the incomplete combustion of natural gas or city gas may be used.

Bath Furnaces

Liquid baths are often used for heating steel in the heat-treating processes. The materials which serve as the heating media are usually salt, lead, and oil. Bath furnaces can be operated within the following ranges of temperatures: mixtures of salts, 350 to 2350 degrees F.; lead, 650 to 1700 degrees F.; and oil up to 500 degrees F. Because of the limitation of operating temperatures, each bath is restricted to certain forms of heat treatment. In general, the advantages of bath furnaces lie in the avoidance of oxidation during heating, in the rapid heating of the work, and in the possibility of obtaining uniform temperatures throughout the work being heated. Liquid bath furnaces are heated by gas, oil, or electricity. Two general methods of heating liquid baths are (1) external heating whereby heat is applied to the outside of the container, and (2) internal heating by means of heating units immersed directly in the liquid bath.

Molten Lead Bath—A bath of molten lead can be used to advantage for heating pieces of steel to any temperature within the range of 650 to 1700 degrees F. The lower limit is dependent upon the melting point of lead, whereas the upper limit is determined by the ability of the container to withstand the heat and the coverings to give adequate protection against oxidation of the lead. The equipment required consists of a furnace and a pot of suitable size and shape for the pieces of steel to be heated. The pot, which is made of cast steel or some heat-resisting alloy, is filled with lead. A covering of charcoal is placed on top of the bath to decrease the oxidation of the lead. Owing to the high specific gravity of molten lead, steel will float in it, and, therefore, must be held below the surface. The advantages of the lead bath for heating steel preparatory to hardening or for tempering are: (1) that uniform temperatures can be obtained throughout the work; (2) that the steel will not become oxidized during the heating period; and (3) that the rate of heating is rapid in the lead bath. This method of heating is particularly favorable in the hardening of broaches, reamers, drills, axes, and many other tools.

Molten Salt Bath—Uniform temperatures throughout steel parts can be secured in baths of molten salts. The salts are heated in a metal pot in a suitable furnace. See Fig. 91. For a temperature range of 1100 to 1650 degrees F., a mixture of equal parts of barium chloride, calcium chloride, and sodium chloride is satisfactory. Other combinations of salts can be used for temperatures as low as 350 degrees and as high as 2350 degrees F. As no appreciable scaling of steel takes place below 1100 degrees F., pieces of steel can be preheated slowly to this temperature in an open-chamber furnace, and then transferred to the molten salt bath where the desired temperature for hardening is obtained. When pieces of steel are removed from the bath, a small amount of salt adheres to the surfaces, and this prevents oxidation during the transfer of the steel to the quenching tank. The heating and quenching of large numbers of small parts are done most conveniently when they are strung on wires or placed in wire baskets. This method of heating is particularly adapted to the hardening of finished machine parts which must be protected from scaling.

Salt baths may be heated internally by means of electrodes suspended in the bath. Alternating current passing between the electrodes heats the bath by the resistance offered by the salt to the flow of the electric current. The molten salt heated in this way rises to the top of the bath, and cooler salt is drawn in to the heating space between the electrodes. The resulting circulation of the molten salt assures a uniform temperature throughout the bath. Longer pot life and accurate control of bath temperatures are advantages of this method of heating.

Oil Bath—A bath of oil can be used for tempering steel parts at temperatures up to 500 degrees F. Mineral oil with a high flash point is satisfactory for this purpose. The oil may be heated in a metal container having any size or shape which will accommodate the work. Electric immersion heaters may be used in the oil or the container may be heated externally by gas or oil fuel. Equipment similar to that shown in Fig. 91 is satisfactory.

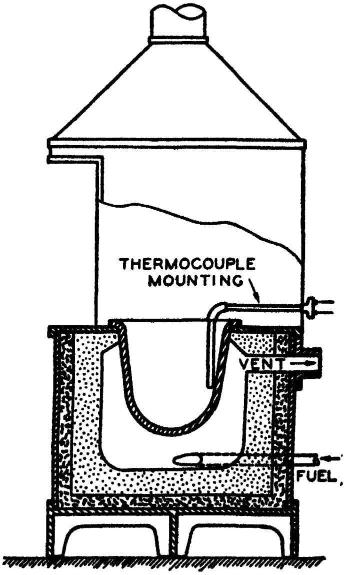


FIG. 91—EQUIPMENT FOR SALT BATH

QUENCHING EQUIPMENT

Quenching follows the initial heating of steel in the hardening process. When a piece of steel which has been heated is immersed in a liquid such as water or oil, the liquid in direct contact with the metal becomes heated to the boiling point, and is then vaporized. This causes the removal of heat from the metal. The specific heat as well as the latent heat of vaporization are significant properties of quenching liquids. The rate of cooling of steel parts in the quenching operation is also dependent upon the speed of movement of the liquid across the surfaces of the steel; hence a rapid circulation of the quenching medium is usually desirable.

The same results are obtained by a vigorous movement of the parts in the quenching bath.

To secure uniform results from the quenching treatment, the liquid is maintained as near as possible to a constant temperature. In tool rooms where relatively small pieces of steel are quenched intermittently, metal tanks containing oil, salt brine, and water are usually satisfactory. A convenient quenching layout for a tool-hardening room is shown in Fig. 92. The large tank contains fresh running water which serves to cool both the brine and oil. Water is supplied through a vertical pipe producing a fountain in which some tools can be quenched most advantageously. The oil quenching bath is provided with a close-fitting cover to extinguish a fire in case the oil should become overheated. The baskets are useful for holding small quenched parts. In large production units, quenching oil is kept at a fairly constant temperature by circulating cold water through coils of pipe in the oil tank, or by circulating the

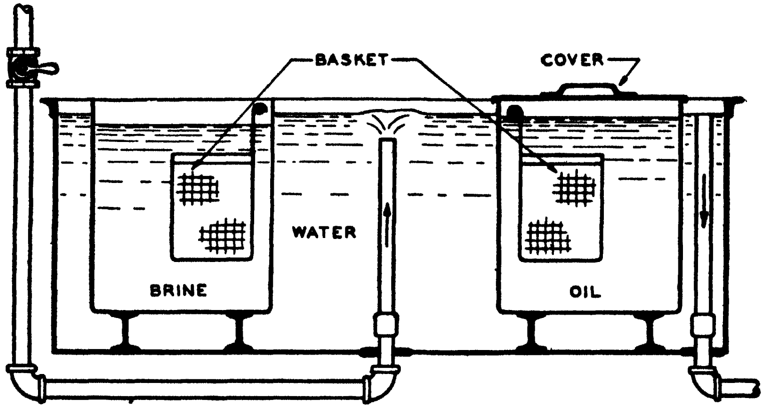


FIG. 92—QUENCHING EQUIPMENT FOR TOOL ROOM

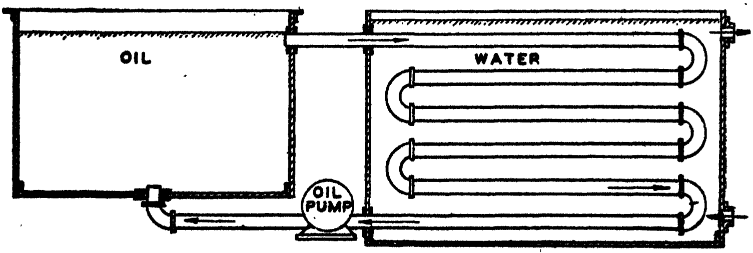


FIG. 93—OIL QUENCHING TANK AND COOLING SYSTEM

oil through pipes in a separate cooling system. Equipment for this purpose is shown in Fig. 93. The size of the quenching tank and the rate of cooling are arranged so as to prevent an appreciable rise of temperature of the quenching oil. A general rule is to provide one gallon of oil for each pound of steel quenched per hour. In carrying out the hardening treatment, it is important that the steel be transferred as quickly as possible from the furnace to the quenching liquid. To facilitate this operation, the quenching tanks are often located directly in front of the furnaces.

Gears which are produced in large numbers are often held flat in automatic presses during the quenching operation. With this equipment, the amount of distortion in the gears is kept to a minimum. Furthermore, the circulation of the quenching oil and the time of immersion are controlled so that uniform properties are regularly obtained in the product.

EQUIPMENT FOR MEASURING TEMPERATURES

In all heat-treating practice, equipment is required for measuring temperatures. It is only by the accurate control of temperatures that the full benefit of heat treatments can be secured. For the measurement of high temperatures in heat-treating operations, the thermoelectric pyrometer is generally used. Mercury thermometers are limited to temperatures below 1000 degrees F.

Thermoelectric Pyrometer

The operation of the thermoelectric pyrometer is based on the principle that an electric current is produced when two wires of different metals are joined at both ends so as to make a complete circuit, and one junction is at a higher temperature than the other. The electromotive force developed in the circuit varies with the difference in temperature of the two junctions. If one junction is kept at a definite or known temperature and some means is provided for measuring the electromotive force developed in the circuit, it is possible to establish the temperature of the other junction. In the practical application of this principle, an electric meter is connected to two wires of dissimilar metals which are welded together to form the hot junction. These two wires are known as a **thermocouple.** The three essential parts of the thermoelectric pyrometer are the thermocouple, the indicating instrument, and the wires leading from the thermocouple to the instrument.

The connections between the wires of the thermocouple and the copper wires leading to the meter form the **cold junctions.** It is necessary to keep the cold junctions at a definite temperature (75 degrees F. for many commercial instruments) or to compensate for any variations from the temperature used in calibrating the instrument. In some installations, the wires leading from the thermocouples to the indicating instrument are of special alloys which have the same thermoelectric characteristics as the couple wires. This allows the cold junctions to be transferred to a point of constant temperature, or to the meter where the cold-end temperature can be measured, and the corrections for variations in cold-end temperatures can be made in the meter readings. The installation shown in Fig. 94 has the thermocouple wires connected to the indicator with cold-end extension wires.

The thermocouples used in heat-treating practice are described as noble-metal and base-metal couples. A **noble-metal couple** consists of one wire of pure platinum and the other of an alloy of platinum and rhodium. This couple will maintain a constant calibration for long periods of service, and is used for temperature measurements up to 2900 degrees F. The wires in the noble-metal couple do not oxidize readily and have relatively high melting temperatures. **Base-metal couples** are made from nickel-chromium wire with nickel-aluminum wire for temperatures up to 1800 degrees F., nickel-chromium wire with copper-nickel wire for temperatures up to 1400 degrees F., and iron wire with copper-nickel wire for temperatures up to 1200 degrees F. When exposed to high temperatures, base-metal couples have a much shorter life than noble-metal couples because they oxidize more readily. To protect the thermocouple wires from mechanical injury, as well as from

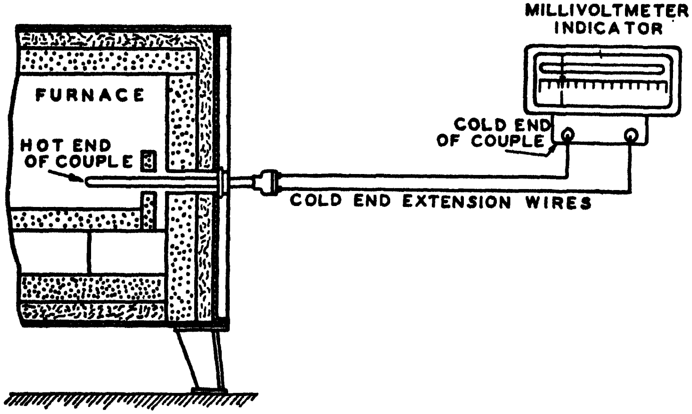


Fig. 94—Installation of Thermoelectric Pyrometer

contamination by furnace gases, they are usually mounted in tubes of metal, fused quartz, or porcelain. A thermocouple mounted in a metal protection tube is shown in Fig. 95.

Two types of instruments are used for measuring the electromotive force generated in a thermocouple circuit. These are designated as the **millivoltmeter type** and the **potentiometer type** of temperature indicator. A millivoltmeter connected to the thermocouple circuit as shown in Fig. 94 will indicate the electromotive force caused by the difference in temperatures of the hot and cold junctions of the thermocouple. The millivoltmeter is calibrated to show directly the temperatures at the hot junction within the furnace.

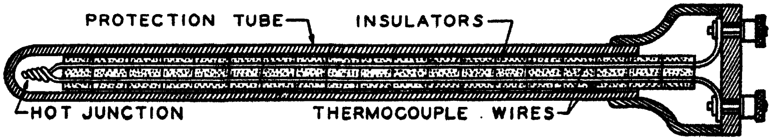


FIG. 95—MOUNTING FOR THERMOCOUPLE

The other method for measuring the electromotive force produced in a thermocouple utilizes the principle of the potentiometer. With the aid of the wiring diagram in Fig. 96, the operation of the potentiometer will now be explained. *A–C* is a thermocouple; *B* is a battery which supplies current through the resistance *D–E–F*; and *G* is a galvanometer which indicates the direction of flow of current in the circuit *A–C–D–E*. The location of point *E* on the resistance *D–F* is adjusted so that the drop in potential between the points *D* and *E* caused by the current from the battery *B* is balanced by the electromotive force developed by the thermocouple. With this adjustment, the galvanometer will show that no current is flowing through the thermocouple circuit. When the electromotive force of the couple changes, the point *E* must be moved along the resistance *F–D* to balance this effect. The variable resistance

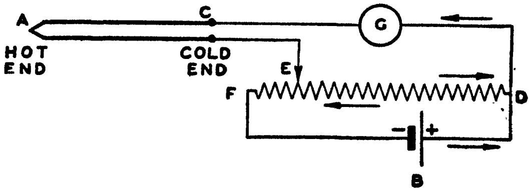


FIG. 96—WIRING DIAGRAM FOR POTENTIOMETER INDICATOR

F–D is calibrated so that the location of point *E* will indicate directly the temperature of the hot end of the thermocouple.

As no current passes through the thermocouple circuit when the potentiometer is balanced, the readings are not affected by changes in the resistance of the thermocouple circuit.

When properly installed and calibrated, the thermoelectric pyrometer indicates the temperature of the hot junction of the thermocouple, and, unless the furnace is uniformly heated, the indicated temperature will represent only that part of the furnace near the thermocouple. To be certain that the material being heated is at the desired temperature, it should have the same brightness as the hot end of the thermocouple or of the protection tube, when viewed through the door of the furnace.

Permanent records of temperatures within heat-treating furnaces can be obtained by using recording pyrometers. Furthermore, these instruments can be arranged to operate signal lights or fuel valves for the close control of furnace temperatures.

Mercury Thermometer

Mercury thermometers can be used to measure temperatures up to 1000 degrees F. The expansion of the mercury is directly proportional to the temperatures which are indicated on the stem of the thermometer. In high-temperature thermometers, the capillary tube above the mercury is filled with nitrogen gas under pressure. These instruments find special application in oil baths for tempering carbon tool steel.

REVIEW QUESTIONS

1. Outline the general classification of heat-treating furnaces.
2. What are the three ways for arranging the heating chamber in hearth furnaces?
3. Describe two types of construction of movable-hearth furnaces.
4. What are the advantages of bath furnaces in the heat treatment of steel?
5. What heat-treating process can be carried out in an oil bath?
6. Describe the quenching equipment used in the heat treatment of steel parts.
7. Explain the principle of operation of the thermoelectric pyrometer.
8. What are the two types of indicators which can be used with thermocouples for measuring temperatures?
9. What conditions are necessary to insure that the material being heated withing a furnace is at the desired temperature?
10. Show on a sketch the complete equipment for measuring temperatures in a hearth furnace.

CHAPTER X

ALLOY STEELS AND THEIR HEAT TREATMENTS

ALLOY CONSTRUCTIONAL STEELS—**Nickel Steels—Chromium Steels—Corrosion- and Heat-Resisting Steels—Nickel-Chromium Steels—Manganese Steels—Silicon-Manganese Steel—Chromium-Vanadium Steels—Molybdenum Steels**—ALLOY TOOL STEELS—**High-Speed Steels—Hot-Work Steels—Wear-Resisting Steels—Non-Deforming Steels—Shock-Resisting Steels**

The two main groups of commercial steels are carbon steels and alloy steels. The properties of carbon steels are related directly to the percentages of carbon which they contain, whereas the properties of alloy steels are dependent upon the presence of metallic elements other than those found in carbon steels or upon a considerable increase in either of the elements silicon or manganese. The principal alloying elements are nickel, chromium, molybdenum, vanadium, manganese, silicon, and tungsten. Each of these elements confers certain qualities upon the steel to which it is added. Some of the alloying elements combine with carbon to form compounds which are present as hard constituents, whereas other elements do not form carbides, but remain in solution in the ferrite at ordinary temperatures. Those elements which on slow cooling form carbides are manganese, chromium, tungsten, vanadium, and molybdenum, whereas elements such as nickel, copper, and silicon remain dissolved in ferrite after slow cooling. The beneficial effects of the special elements on the properties of steel are dependent upon certain principles which will now be considered.

Small sections of carbon steel can be heat treated so as to obtain a tensile strength and hardness only slightly inferior to those obtained with alloy steels, but large sections of carbon steel can not be hardened throughout by a quenching treatment. This limitation of the hardening of carbon steel is due to the speed of transformation of the austenite to soft constituents even during fairly rapid cooling from temperatures above the critical range. Practically all the alloying elements when dissolved at the quenching temperature retard the transformation rate, and thereby contribute to the deep hardening of the steel. Larger sections of alloy steel can therefore be hardened to greater depths than corresponding sections of carbon steel. See Figs. 77 and 78 in Chapter

VIII. This general characteristic of the special alloying elements is of particular advantage in securing the desired properties throughout hardened and tempered steels. When liquid quenching is impracticable because of intricate shapes or differences in connected sections in the steel parts, suitable alloy compositions may be selected which will permit the desired properties to be obtained with air cooling.

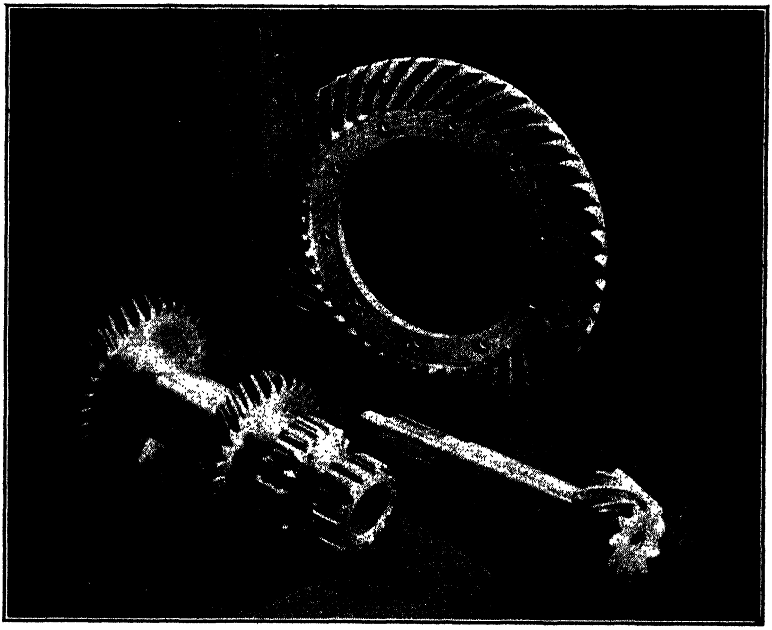
Some of the alloying elements retard the growth of the grains in steel at temperatures above the critical range. In particular, vanadium, molybdenum, tungsten, and chromium have a beneficial effect in steel because of this influence. A wider range of quenching temperatures is thus made possible, and a more uniform structure is obtained after heat treatment.

Higher tempering temperatures are usually required for alloy steels than for carbon steels because martensite, obtained after quenching, is less readily changed to secondary troostite and sorbite when the alloying elements are present. The high tempering temperatures bring about the removal of internal stresses with a corresponding improvement in ductility and resistance to suddenly applied loads. Carbon steel becomes softened appreciably when heated to 500 degrees F. after hardening, but the hardness of some of the alloy tool steels is retained after heating to 1000 degrees F.

Because of the difficulty and expense of heat treating long lengths of steel in structural sections and plates, some alloy steels are used in the condition as rolled. Furthermore, the beneficial effects of heat treating would be destroyed when these steels are welded. Most of the alloy steels, however, are quenched and tempered to obtain the full benefit of the alloying elements. All the heat-treating processes which have been described for carbon steels (refer to Chapter VIII) are applicable to alloy steels. The temperatures, lengths of time for heating, and rates of cooling used in these processes vary with the different chemical compositions of the special steels and with the properties desired.

ALLOY CONSTRUCTIONAL STEELS

During the past thirty years, the use of alloy steels has been extended to all fields of engineering practice. Because of their superior physical and chemical properties, the alloy steels are employed for many purposes where the carbon steels are inadequate. High properties are frequently required in structural sections and plates which are difficult to heat treat by quenching and tempering; for these purposes, alloy steels are supplied in the condition as rolled or after a normalizing treatment. Large tonnages of these unhardened steels are used in bridges, railroad cars, truck bodies, skip hoists and cages for mines, mine cars, buckets for handling materials, long booms on cranes and other structures where weight per unit strength is an important consideration. When these steels are fabricated by welding without stress relieving, the carbon content usually does not exceed 0.15 per cent. As carbon has a most pronounced hardening influence, it must be kept low in steels which are to be welded. Otherwise, hardened areas with unfavorable ductility will be produced in the vicinity of welds. For riveted construction, steels containing as high as 0.35 per cent carbon may be supplied. Many different combinations of alloying elements are utilized in the making of these seels. Copper is added to confer corrosion resistance, and other special elements include nickel, molybdenum, chromium, and vanadium. Whereas the yield point of carbon steel ordinarily used in structural sections is about 38,000 lb. per sq. in., a minimum yield point of 50,000 lb. per sq. in. is generally specified for these special steels.



Courtesy of Republic Steel Company

FIG. 97—ALLOY STEEL GEARS

The alloy steels which are heat treated before being put in service may be divided in two general groups known as carburizing grades and full-hardening grades. The carburizing steels are all low in carbon (usually less than 0.25 per cent) and the full-hardening steels are higher in carbon (usually above 0.35 per cent). Alloy steels are often preferred for parts that require a hard wear-resisting case and a tough, ductile core. In the *S.A.E.* classification (refer to Table III in Chapter IV) many of the alloy steels in the lower carbon range are well suited for case-hardened parts. The full-hardening alloy steels are generally quenched in oil, as this practice produces sufficient depth of hardening and also causes less distortion than when water quenching is employed. The compositions, heat treatments, and properties of some of the important alloy constructional steels will now be discussed.

Nickel Steels

The beneficial effect of nickel in steel was discovered many years ago, and some of the early alloy structural steels contained nickel as the chief alloying element. Nickel occurs in steel in solution either in the austenite or in the ferrite. Additions of nickel cause an increase in the strength of steel without appreciably decreasing its ductility in the annealed or in the hardened and tempered condition. The presence of increasing proportions of nickel results in a continuous lowering of the critical temperatures. For nickel steels containing up to 5 per cent, each 1 per cent of nickel lowers the critical range on heating about 20 degrees F. below the corresponding range for carbon steels. Lower temperatures are therefore used in the heat treatments for nickel steels than are required for carbon steels with the same carbon content. Owing to the lower quenching temperatures, less scaling, warping, and cracking of parts made of nickel steels occur during heat treating.

The group of nickel steels which is used most extensively contains 3.25 to 3.75 per cent nickel (*S.A.E.* 2300 series). These alloy steels are available with the carbon ranging from 0.10 to 0.55 per cent as indicated in Table III. The nickel steels with 0.10 to 0.25 per cent carbon are used for machine parts which are to be case hardened. Other nickel steels containing 0.25 to 0.55 per cent carbon are employed in the hot-rolled or normalized condition for highly stressed bridge members, and in the hardened and tempered condition for machine parts requiring high strength and toughness. Gears having large sections are often made of steel containing approximately 3.50 per cent nickel and 0.50 per cent carbon.

Steels containing over 25 per cent nickel retain an austenitic structure at room temperature and are used in parts requiring a non-magnetic material of high strength. As the nickel content is increased above 30 per cent, the coefficient of linear expansion at normal temperatures is lowered rapidly until it reaches a minimum of nearly zero, when the alloy contains between 35 and 36 per cent nickel. Because of this property, the high-nickel steels are used for parts of scientific instruments, measuring tapes, watches, and clocks.

Chromium Steels

Chromium occurs in steel as the double carbide of chromium and iron. As chromium alone does not harden iron, it is necessary to have sufficient carbon present in steel to form the hard compounds. The outstanding effects of chromium are to increase the hardness and strength of steel after heat treatment, and to make the steel more resistant to corrosion. The transformation of austenite to other constituents is retarded by chromium, so that martensite is readily obtained in heavy sections of chromium steel after a hardening treatment. For this reason chromium steels can be hardened with a slower speed of cooling than corresponding carbon steels. Increasing percentages of chromium in steel raise the critical temperature slightly above those for carbon steels, which accounts for the higher temperatures used in the heat treatments for chromium steels.

Chromium steels having a low carbon content (*S.A.E.* 5120) are used for parts which are to be case hardened. The heat treatments for these steels are similar to those for plain carbon steels except that the quenching temperatures are about 50 degrees higher than the temperatures used for corresponding carbon steels. The chromium steels with a medium carbon content (*S.A.E.* 5140 and *S.A.E.* 5150) possess greater strength and depth of hardening after heat treating than can be obtained in plain carbon steels having the same carbon content. These alloy steels are usually quenched in oil. An alloy steel which is used chiefly for parts of ball and roller bearings contains 0.95 to 1.10 per cent carbon and 1.20 to 1.50 per cent chromium (*S.A.E.* 52100). This steel is quenched in oil from temperatures of 1500 to 1550 degrees F. and is tempered to the desired hardness.

Corrosion- and Heat-Resisting Steels—Steels containing over 11 per cent chromium possess favorable resistance to attack by various corroding influences, and are employed extensively in equipment for dairies, bakeries, laundries, and chemical plants, as well as for decorative purposes. These steels also resist deterioration at relatively high temperatures and are applied generally in furnace construction.

One type* of special corrosion-resisting steel contains 11 to 14 per cent chromium with a maximum carbon of 0.10 per cent. The most favorable properties are obtained when this steel is quenched in oil from 1800 degrees F. and tempered to the desired hardness. This steel is the most economical of the "stainless" group, forges well, and has fair machining properties. It may be used satisfactorily for temperatures up to 1400 degrees F.

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* The resistance to corrosion of the chromium alloys is probably due to the formation of a very thin film of oxide on the surface of the metal, which retards further attack by corrosive agents. At high temperatures, this surface film increases in thickness, eventually forming a continuous, firmly adherent scale which serves to protect the underlying metal from further oxidation.

Another type of "stainless" steel containing 11 to 14 per cent chromium and about 0.35 per cent carbon is used for cutlery, surgical instruments, and other purposes where hard edges are required. Maximum resistance to corrosion is obtained when this steel is ground and polished after heat treating. The heat treatment consists of heating to 1825 degrees F., quenching in oil, and tempering about 400 degrees F. A martensitic structure is obtained after this heat treatment. When this steel is used in furnace equipment, scaling takes place above 1400 degrees F.

Large quantities of steel containing 16 to 20 per cent chromium and less than 0.12 per cent carbon are produced for corrosion-resisting purposes. Steel of this composition can not be hardened appreciably by quenching in water, and heat treating is not necessary to develop its best corrosion resistance. This chromium steel is manufactured chiefly in the form of sheets and strips. It has a tensile strength of 75,000 lb. per sq. in. with an elongation of 25 per cent and a Brinell hardness of 175. For heat-resisting purposes, this steel is satisfactory up to 1550 degrees F.

Another steel in this group, which is widely used, contains approximately 18 per cent chromium and 8 per cent nickel with the carbon usually less than 0.15 per cent. This steel is commonly known as the 18-8 alloy and is marketed under many trade names. When steel of this composition is quenched at any temperature above 1850 degrees F. in oil or water, a relatively soft, austenitic structure is obtained. An increase in hardness is brought about by cold working the metal during forming and deep-drawing operations. In addition to its resistance to atmospheric corrosion, steel of this analysis does not scale appreciably when heated to temperatures up to 1800 degrees F. The tensile strength of the 18-8 alloy after heat treating is 85,000 lb. per sq. in. with an elongation of 60 per cent and a Brinell hardness of 130.

Alloy steels containing 23 to 30 per cent chromium with the carbon less than 0.35 per cent are used principally for service at temperatures between 1500 and 2100 degrees F. Furnace parts, annealing boxes, and other equipment requiring resistance to high temperatures are often made of these steels which are supplied in the form of sheets, plates bars, and tubing.

Nickel-Chromium Steels

The specifications of the *Society of Automotive Engineers* (Table III) include four groups of nickel-chromium steels having a carbon range of 0.10 to 0.55 per cent. The nickel content of these constructional steels is 1½ to 4 times the chromium content. Each of the alloying elements contributes its beneficial effects, and, as a result, steels having high strength and deep-hardening power are secured. Like other alloy steels, the nickel-chromium steels containing up to 0.25 per cent carbon are ordinarily used for carburized parts such as gears, worms, pinions, bushings, and cams. Within the carbon range of 0.25 to 0.35 per cent, these alloy steels may be quenched in water, but, above 0.35 per cent carbon, they are generally quenched in oil for gears, shafts, pins, and other machine parts. Those steels with low carbon content are used for carburizing purposes, and those with the higher carbon content are used for heat-treated forgings and shafting of large size.

Manganese Steels

Those steels containing over 1.50 per cent manganese are designated as manganese alloy steels. Manganese improves the strength of steel in both the hot-rolled and heat-treated condition. In the *S.A.E.* T 1300 series, steels containing 0.30 to 0.40 per cent carbon are employed for shafts, pins, bolts, and many other machine parts. The manganese alloy steels with a carbon range of 0.40 to 0.55 per cent are used extensively in oil-hardened gears, axles, shafts and other parts where high strength combined with fair ductility is required.

Increasing proportions of manganese in steel cause a retarding effect on the transformation of austenite during cooling. When the manganese content is 11 to 14 per cent together with a carbon content of 1.00 to 1.40 per cent, a steel is produced with a structure composed largely of austenite at room temperature. During the slow cooling of the high-manganese steel from the casting temperature, some cementite separates with the austenite and causes the steel in this condition to be extremely hard and brittle. When cast manganese steel is heated to 1800 degrees F., the cementite dissolves in the austenite, and with rapid quenching from this temperature in cold water, the cementite is prevented from again separating out. Because of its austenitic structure, manganese steel is non-magnetic. Cast specimens after heat treating have a tensile strength of about 100,000 lb. per sq. in. with an elongation of 30 per cent and a Brinell hardness of 200. As manganese steel is extremely difficult to machine by any methods other than by grinding, it is desirable to cast or forge the parts to approximately the finished shape and size.

One of the valuable properties of austenitic manganese steel is that its hardness is increased rapidly by cold working. It is due to this characteristic that manganese steel after heat treating is particularly advantageous for parts of equipment which are subjected to wear by a pounding or rolling action. Some typical examples of service of this kind are the plates for rock crushers; frogs, switches, and crossings for railroad tracks; dipper teeth and lips for excavating machinery; and gears, racks, and sheaves for many purposes.

Silicon-Manganese Steel

An alloy steel containing approximately 0.50 per cent carbon, 2.00 per cent silicon, and 0.70 per cent manganese (*S.A.E.* 9250) is used mainly for leaf and coil springs. This steel is hardened by quenching at temperatures of 1500 to 1600 degrees F. in oil, and is then tempered at 850 degrees F.

Chromium-Vanadium Steels

Vanadium is often added to steel in combination with chromium. The *S.A.E.* 6100 series contains 0.80 to 1.10 per cent chromium and about 0.18 per cent vanadium. Refer to Table III. This combination of alloying elements produces steels having high strength as well as resistance to wear and fatigue. The chromium-vanadium steels are available in a number of ranges of carbon content. Those having a low carbon content (up to 0.25 per cent) are used for case-hardened parts, and the steels with a higher carbon content (0.25 to 0.55 per cent) are usually hardened and tempered for parts which are subjected to severe service. The properties obtained after heat treating ¾-inch round bars of *S.A.E.* 6145 steel are given in Table XI. It is of interest to compare these properties with the results obtained after heat treating a carbon steel having the same carbon content, as given in Table IX in Chapter VIII.

Molybdenum Steels

Molybdenum tends to inhibit grain growth in steel and increases the range of temperature within which steel can be hardened. The critical temperature on heating for molybdenum steel is somewhat higher than that for the corresponding carbon steel. Molybdenum causes an increase in the tensile strength and hardness of steel without loss of ductility and without rapidly decreasing its machinability. Although some steels contain molybdenum as the only alloying element, molybdenum is often added to steel with chromium (*S.A.E.* 4100 series) or with nickel (*S.A.E.* 4600 series). In all the *S.A.E.* compositions for molybdenum steels, the molybdenum content varies from 0.15 to 0.40 per cent in 10-point ranges. With a carbon content of 0.25 to 0.35 per cent, the steels in the *S.A.E.* 4100 series are of the water-hardening type, and are used for airplane tubing, bolts, studs, axles, shafts, connecting rods, and similar applications. With the carbon above 0.35 per cent, the steels in this series become oil-hardening, and are used for heavy-duty gears, shafts, bolts, and similar parts. In the *S.A.E.* 4600 series, containing 1.65 to 2.00 per cent nickel with molybdenum, those steels in the low-carbon range are case hardened and in the high-carbon range are directly oil quenched. An important application of these steels is for heat-treated gears.

TABLE XI

PROPERTIES OF *S.A.E.* 6145 STEEL AFTER HEAT TREATING

Heat Treatment for Specimens ¾ In. in Diameter	Yield Point, Pounds per Square Inch	Tensile Strength, Pounds per Square Inch	Elongation, Per Cent in 2 Inches	Reduction of Area, Per Cent
Furnace cooled from 1600° F.....	54,150	92,850	27.5	53.5
Quenched in oil from 1600° F. tempered at 800° F...............	203,175	207,500	12.0	47.0
Quenched in oil from 1600° F. tempered at 900° F...............	179,900	186,450	13.5	49.0
Quenched in oil from 1600° F. tempered at 1000° F..............	168,800	175,350	15.0	50.5
Quenched in oil from 1600° F. tempered at 1100° F..............	152,450	159,275	17.0	53.0
Quenched in oil from 1600° F. tempered at 1200° F..............	127,750	136,500	20.0	60.0
Quenched in oil from 1600° F. tempered at 1300° F..............	102,400	110,050	25.0	66.5

ALLOY TOOL STEELS

The important alloying elements in steels used for cutting and forming metals or other materials are tungsten, chromium, vanadium, molybdenum, and manganese. Tungsten inhibits grain growth, increases the depth of hardening of quenched steel, and confers the property of remaining hard even when heated to a red color. Chromium has a pronounced hardening effect when present with sufficient carbon.

Vanadium and molybdenum aid in obtaining a fine grain structure in tool steel. Manganese intensifies the hardness of steel when it is present in sufficient proportion together with other hardening elements. Many different combinations of these alloying elements are used in the manufacture of steel for tools. As a rule, alloy tool steels have low thermal conductivity and high thermal expansion. Consequently, these steels should be heated slowly and uniformly, and should be held at the hardening and tempering temperatures sufficiently long to insure uniform heating throughout the sections. Best results are obtained when tools are thoroughly preheated to lower temperatures before placing in a furnace held at the quenching temperature. All tools should be quenched in a manner to reduce the amount of warpage. Long slender pieces are quenched vertically on end. Furthermore, all hardened tools should be removed from the quenching bath while they are still warm (approximately 125 to 150 degrees F.) and transferred to the tempering furnace before they have cooled to room temperature.

In the following discussion of the different groups of alloy tool steels, typical average analyses are given rather than limits in the percentages of the different elements. Actual analyses of commercial steels vary considerably for the same type of steel. Also, the heat treatments specified may require adjustment to conform with changes in the composition of the steel or with special requirements of the particular work.

High-Speed Steels

When a hard material is machined at high speeds with heavy cuts, sufficient heat may be developed by friction of the material on the tool to cause the temperature of the cutting edge to reach a red heat (over 1000 degrees F.). This temperature would soften some tool steels to the extent of destroying their cutting ability. However, certain highly alloyed steels, designated as high-speed steels, are available which retain their cutting edges at high temperatures. The changes in hardness resulting from reheating carbon tool steel containing 1.10 per cent carbon after quenching in water from 1450 degrees F. and a tungsten high-speed steel after quenching in oil from 2350 degrees F. are shown in Table XII. The hardness of the carbon tool steel decreased continuously as the temperature was raised. In this steel, the martensite produced on quenching was gradually transformed to softer constituents. On the other hand, the hardness of the high-speed steel decreased gradually as the temperature was raised to about 700 degrees F. and then increased on further heating to about 1000 degrees F. This increase in hardness (known as secondary hardening) was caused by the transformation of austenite, retained in the steel after quenching, to martensite. The advantage of high-speed steel is largely its ability to retain a high hardness when heated to relatively high temperatures.

TABLE XII

HARDNESS OF QUENCHED AND TEMPERED STEELS

Temperature Degrees F.	Carbon Tool Steel Rockwell Hardness	High-Speed Steel Rockwell Hardness
As quenched	C 67	C 66
300	C 65	C 65
400	C 64	C 64
500	C 61	C 62
600	C 57	C 61
700	C 54	C 61
800	C 48	C 61
900	C 45	C 63
1000	C 39	C 64
1100	C 33	C 64
1200	C 25	C 57
1300	C 19	C 47

A composition of high-speed steel which is used extensively for lathe planer, and shaper tools, drills, and milling cutters includes approximately 0.70 per cent carbon, 18 per cent tungsten, 4 per cent chromium, and 1 per cent vanadium. Before this steel is machined or hardened, it is annealed by heating throughout to 1600 degrees F. and cooling slowly. In the hardening treatment, the high-speed steel is preheated slowly in one furnace to 1550 degrees F. and is then transferred to another furnace where it is heated rapidly to 2350 degrees F. The preheating is necessary to decrease the liability to cracking because of the low thermal conductivity of the steel, and to shorten the time of exposure at the higher temperature. A sufficiently high temperature must be reached before quenching to dissolve a large portion of the tungsten and chromium carbides in the steel. Furthermore, the length of time at which the steel is held at the high temperature must be limited to avoid excessive grain growth. Small pieces of this steel (less than ½ inch in thickness) may be quenched in still air, but tools of high-speed steel are usually quenched in oil. The most favorable combination of hardness and toughness is obtained by tempering this steel at 1050 degrees F. At this temperature, internal stresses resulting from quenching are removed and all retained austenite is changed to the harder constituent, martensite.

Other compositions of high-speed steels have tungsten 14 to 22 per cent, chromium 1 to 4 per cent, vanadium 1 to 4 per cent, cobalt 4 to 12 per cent, and molybdenum 4 to 8 per cent. A high-speed steel which has recently replaced the high-tungsten alloy to some extent contains 8 per cent molybdenum, 4 per cent chromium, 1 per cent vanadium, and 1½ per cent tungsten. This steel is decarburized when it is heated to forging and heat-treating temperatures without protection. When grinding allowances are not sufficient to remove the decarburized surfaces, tools made of this steel are heated in furnaces with controlled atmospheres or are protected by coatings. These tools are heated to 2250 degrees F., quenched in oil, and tempered at 1050 degrees F.

Hot-Work Steels

The dies used in equipment for working steel in the hot condition are subjected to severe abrasion and high pressures. Die steels must therefore possess high hardness and strength at forging temperatures. Die blocks and die inserts which are ordinarily used in forging hammers are often made of steel containing 0.60 per cent carbon, 1.50 per cent nickel, 0.75 per cent chromium, and 0.25 per cent molybdenum. This steel is hardened by quenching in oil from 1550 degrees F. and is tempered about 800 degrees F.

Several grades of hot-work steel are used in dies for forging machines. An alloy steel containing 0.30 per cent carbon, 14.00 per cent tungsten, 3.50 per cent chromium, and 0.50 per cent vanadium resists deformation at high temperatures. The heat treatment for this steel required heating to 2250 degrees F., quenching in oil, and tempering at 1050 degrees F. Another alloy steel which is used in gripper and header dies for forging machines contains 0.55 per cent carbon, 4.00 per cent chromium, 1.00 per cent vanadium, and 0.50 per cent molybdenum. This steel is hardened by cooling in air from 1650 degrees F. and is tempered at 1050 degrees F.

Wear-Resisting Steels

A group of steels having great resistance to wear and abrasion are designated as high-carbon, high-chromium steels. In this group, two compositions have been widely adopted; one contains 2.25 per cent carbon with 12 per cent chromium, and the other contains 1.50 per cent carbon with 12 per cent chromium, 0.75 per cent molybdenum, and 0.25 per cent vanadium. In this group, steels with the higher carbon content are hardened by quenching in oil from a temperature about 1775 degrees F., and steels with the lower carbon are cooled in air from about 1850 degrees F. Both types harden all the way through with a structure containing many complex carbides which impart great resistance to wear. The oil-hardening steels have slightly higher maximum hardness and superior wear-resisting properties. On the other hand, the air-hardening type has better resistance to impact as well as better non-deforming and machining characteristics than the oil-hardening type. These steels have low thermal conductivity and should be heated very slowly. Furthermore, they tend to decarburize readily at high temperatures; hence should be heated in furnaces with controlled atmospheres or packed in cast-iron borings. These steels are tempered at temperatures about 400 degrees F. to obtain maximum hardness or about 800 degrees F. to obtain maximum toughness. The high-carbon, high-chromium steels are particularly advantageous for blanking, forming, and trimming dies, wire-drawing dies, and plug gages.

Non-Deforming Steels

Some tools such as punching dies, forming dies, threading dies, and gages, which can not be ground all over after heat treating, are made of steel in which the minimum amount of change in size and shape takes place during the hardening and tempering operations. To meet this requirement, an alloy steel containing 0.95 per cent carbon, 1.15 per cent manganese, 0.50 per cent chromium, 0.50 per cent tungsten, and 0.20 per cent vanadium is often selected. Tools made of this steel are hardened by heating very slowly to 1450 degrees F. and quenching in oil. The tools are removed from the quenching bath while they are still warm, and are tempered immediately at 350 degrees F.

Shock-Resisting Steels

Several compositions of alloy tool steel are used for chisels and punches which are subjected to shock and severe fatigue stresses. One grade of steel for this purpose contains 0.50 per cent carbon, 2.25 per cent tungsten, 1.50 per cent chromium, and 0.25 per cent vanadium. Tools made of this steel are quenched in oil from 1700 degrees F. and are tempered about 500 degrees F. Another grade of shock-resisting steel, known as silicon-manganese tool steel, contains 0.55 per cent carbon, 2.00 per cent silicon, 0.80 per cent manganese, and 0.30 per cent molybdenum. Punches and chisels made of this steel are heat treated by quenching in brine from 1550 degrees F. and are tempered at 350 degrees F. Silicon-manganese steel is decarburized rapidly even in a smoky atmosphere, hence this steel should be heated as rapidly as possible to the quenching temperature after being thoroughly preheated.

REVIEW QUESTIONS

1. Explain the greater depth of hardening of steels containing the alloying elements.
2. Why are the temperatures used in heat treating alloy steels different from those used in heat treating carbon steels with corresponding carbon content?
3. What special properties are obtained in steels containing over 25 per cent nickel?
4. What is the effect of chromium on the critical temperatures of steel?
5. State the compositions and uses of four types of corrosion-resisting steels.
6. What physical constituents are present in manganese steel with 13 per cent manganese before and after heat treating?
7. What characteristic of manganese steel makes this metal particularly suited for resisting wear?
8. State the composition and heat treatment for one high-speed steel.
9. What type of steel is most satisfactory for chisels to be used in air-operated hammers?
10. Specify the steel for dies which must be hardened with the minimum change in dimensions.

CHAPTER XI

PROCESSES AND EQUIPMENT FOR WELDING STEEL

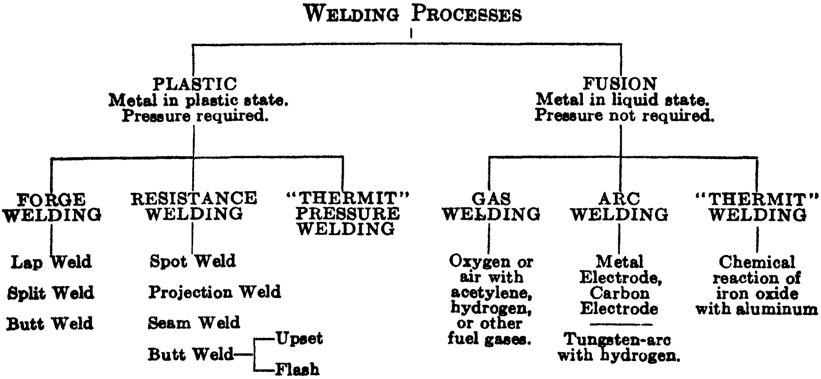
PLASTIC WELDING PROCESSES—**Forge Welding—Resistance Welding—"Thermit" Pressure Welding**—FUSION WELDING PROCESSES—**Gas Welding —Safe Practices—Equipment and Procedure for Gas Welding—Brazing—Oxygen Cutting—Arc Welding—"Thermit" Welding—Hard Facing**

The welding processes are employed extensively in the construction of aircraft, automobiles, ships, railroad cars, buildings, pipe lines, tanks, metal furniture, industrial machinery, farm implements, and other equipment. Since the adoption of welding as a dependable method for joining metals, many improvements have been brought about in the fabrication of steel products. Welding is being used to advantage not only in the manufacture of new products, but also in maintaining and repairing machinery and other equipment.

The processes which are used in welding steel may be classified into two main groups, which are designated as plastic welding and fusion welding. In the first group are those processes which require that the pieces of steel be heated to a plastic state and then forced together by external pressure. This procedure is used in forge welding, resistance welding, and "thermit" welding in which pressure is required. In the second group are gas welding, arc welding, and "thermit" welding. In each of the fusion welding processes, the material at the joint is heated to a molten state and allowed to solidify. A classification of the principal welding processes is presented in Table XIII. The terms used in describing various forms of joints and welds are given in Fig. 98.

The surfaces which are to be joined by any of the welding processes must be sufficiently clean so that cohesion will take place when the metals are in a plastic or fluid state. The presence of oxides on the surfaces which are to be welded interferes with the joining of the metals. This condition is more critical with the plastic welding processes than with the fusion welding processes, because the oxides and impurities may be floated out of the joints during fusion welding. As oxidation proceeds more rapidly with an increase in temperature, special care is taken to prevent the formation of oxides, or to assist in their removal at the welding temperatures. In some operations materials known as fluxes are applied to the parts being welded to dissolve the oxides and thus permit clean, metallic surfaces to come in contact, to aid the flow of the weld metal by reducing its surface tension, and to protect the weld metal from further oxidation.

TABLE XIII



PLASTIC WELDING PROCESSES

When steel is heated, it gradually becomes more plastic until melting occurs. At temperatures in the upper part of the plastic range, the metal can be welded readily with the aid of mechanical pressure. The higher the carbon content of the steel, the more limited is the range of temperature over which plastic welding can be accomplished. Therefore, as the carbon content of the steel increases, more care must be exercised in obtaining the correct welding temperatures for producing sound welds. The three commercial processes which are based on the plastic welding principle are forge welding, resistance welding, and "thermit" welding in which mechanical pressure is required.

Forge Welding

A forge weld is made by hammering together the ends of two bars which have been formed to the correct shape and heated to a welding temperature in a forge fire. The method of preparing the pieces of metal for welding is known as **scarfing.** This involves the shaping of the ends of the pieces to be welded so that they will unite at the center when they are brought together. With this provision, any oxide or slag which is attached to the surfaces will be forced out as the welding proceeds from the center to the outside edges. Furthermore, the metal in the upset scarfed portions provides an enlarged section at the weld which is finally

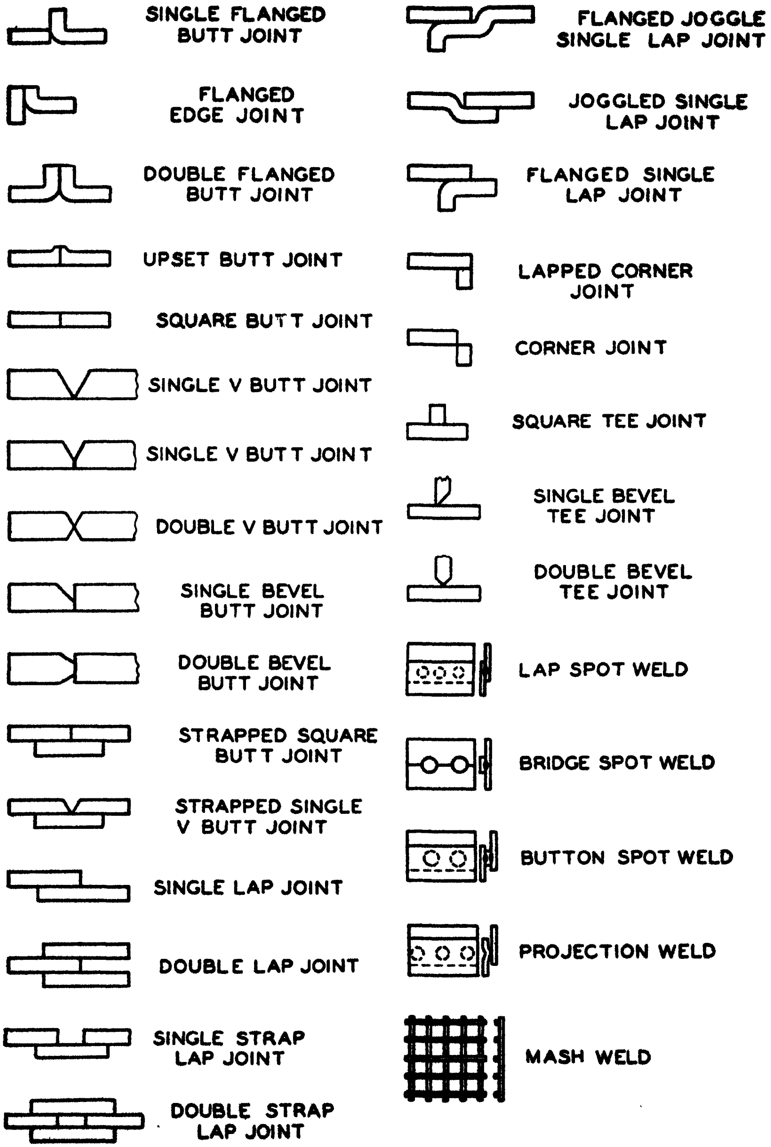


Fig. 98—Forms of Joints and Welds

worked down to the desired size. The methods of scarfing for different types of forge welds are shown in Fig. 99.

A forge fire is often used for heating wrought iron and steel preparatory to welding. The forge consists of a cast-iron hearth with a bowl or depression in the center for the fire. In the bottom of this bowl is an opening through which air is supplied at a low pressure for the combustion of the fuel. Some provision is usually made for the removal of the waste gases from above the hearth. The fuel used on the forge is either coke or a good grade of bituminous coal.

When oxygen of the air comes in contact with pieces of hot iron, a scale (oxide of iron) forms on the surfaces. Oxidation becomes more rapid as the temperature increases. The presence of this scale interferes with welding; hence precautions are taken to decrease the oxidizing action. By maintaining a thick fuel bed on the forge, the oxygen of the air blast is more completely consumed than when a thin fuel bed is used to heat the metals for welding. An additional protection to the metal is a coating of flux which covers the surfaces of the metal and, by excluding the air, prevents oxidation. The flux also dissolves any iron oxide which is present and assists in the removal of this scale from the weld. Fluxes which are commonly used in forge welding consist of clean quartz sand, or salammoniac with borax.

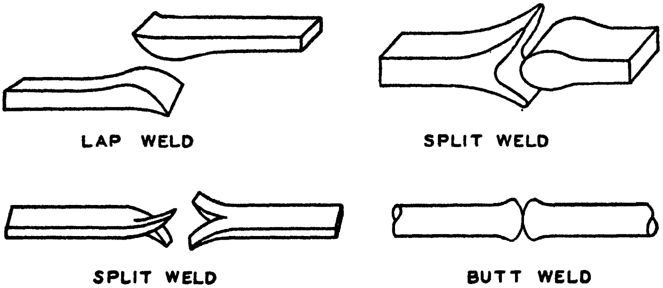


FIG. 99—METHODS OF SCARFING

The parts to be welded are heated slowly in the forge fire to insure a uniform temperature at the scarfed ends of the bars. When the desired temperature is reached, the pieces are hammered together on an anvil. If the heating is continued too long, a coarse grain structure will be produced in the steel. Rapid and thorough working of the metal is essential to the production of sound and strong welds.

Resistance Welding

In the resistance welding process, the pieces of steel to be joined are heated to a plastic state over a limited area by an electric current, and mechanical pressure is used to complete the welds. The important variables in resistance welding are current, time, and pressure. Alternating current has been found most convenient for this purpose as it is possible to obtain any desired combination of current and voltage by using suitable transformers. The material to be welded is clamped between copper electrodes which conduct the low-voltage current to the metal at the joint. The heat developed by the current is in proportion to the electrical resistance of the joint. As the location of maximum resistance is at the surface of contact of the pieces of metal being welded, the highest temperature will be produced directly at the joint. This condition is favorable to the production of satisfactory welds.

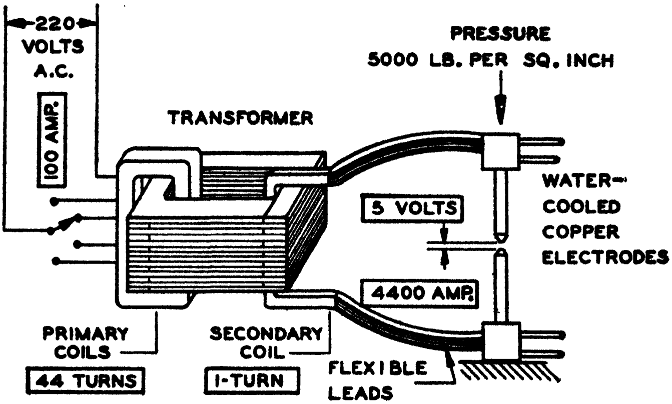
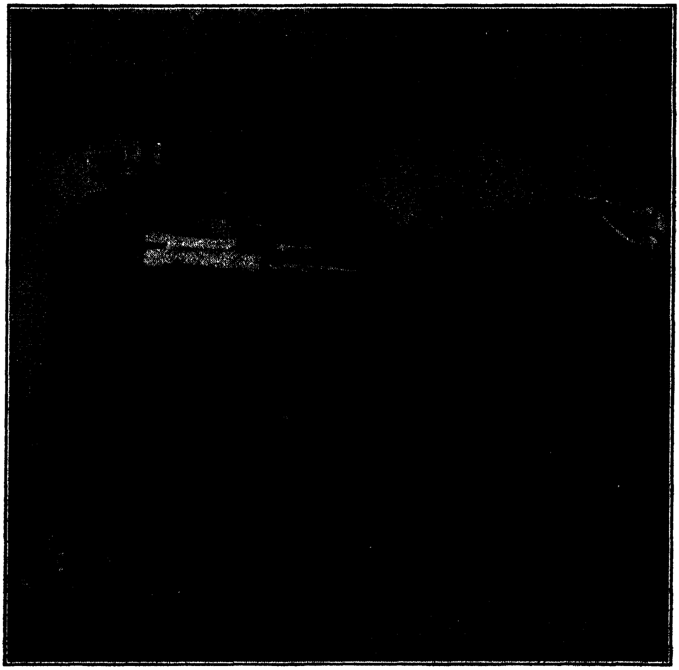


FIG. 100—DIAGRAM OF ELECTRICAL CIRCUIT FOR RESISTANCE SPOT WELDER

The machine used for making resistance welds contains a transformer for reducing the high voltage of an alternating-current power line to 12 volts or less, a clamping device for holding the pieces while they are being welded, and a mechanical means for forcing the pieces together to complete the weld. A diagram of the electrical circuit for a resistance welder is shown in Fig. 100. The amount of current supplied to the weld is determined by the size and shape of the material, and will range from 40 to 120 kilowatts for each square inch of area. In machines which are operated continuously, the electrodes are cooled by water circulating through hollow electrodes.

The four types of welds which are made by the electric resistance process are butt welds, spot welds, projection welds, and seam welds. In the making of butt welds, the current is passed through two pieces of steel which have been placed end to end or edge to edge in a welding machine. The joining of the two ends of a single piece of metal which has been formed into a circular shape can likewise be accomplished by this method. A machine for butt welding steel bars is shown in Fig. 101. The procedure which is generally followed in making butt welds consists of bringing the surfaces to be joined lightly in contact, with the current on, until a violent arcing takes place at the joint, and the metal in the vicinity of the contact surfaces becomes heated to a welding temperature. At this time the current is interrupted, and the pieces are moved together with a quick positive motion which spreads out the metal at the edges to form a small fin on each side of the joint. This procedure is known as **flash welding** to distinguish it from the slower method of supplying the heat gradually to the pieces after they are brought in contact. In the latter method, known as **upset welding**, a considerable upsetting of the metal takes place at the weld. The size of pieces of steel which can be butt welded is practically unlimited. Materials having a diameter as small as $\frac{1}{16}$ inch and as large as 8 inches have been successfully welded



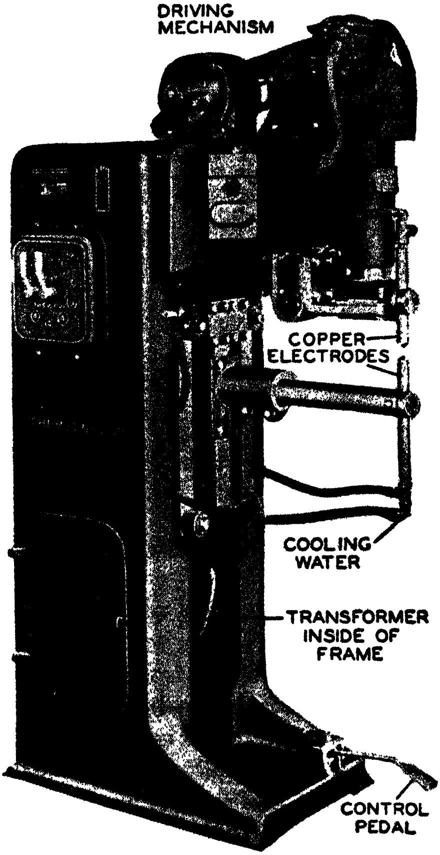
Courtesy of Thomson-Gibb Electric Welder Company

FIG. 101—ELECTRIC RESISTANCE BUTT WELDER

The clamps for holding the work at the upper left side of the welder are operated by foot pedals. The handle on the extreme right is used to bring together the pieces to be welded. An electrical contact button on the handle applies the current.

by the resistance process. Sheet steel less than $\frac{1}{16}$ inch in thickness is being welded in lengths up to 120 inches. Structural sections of large size and steel tubing up to 20 inches in diameter are being welded regularly by this process.

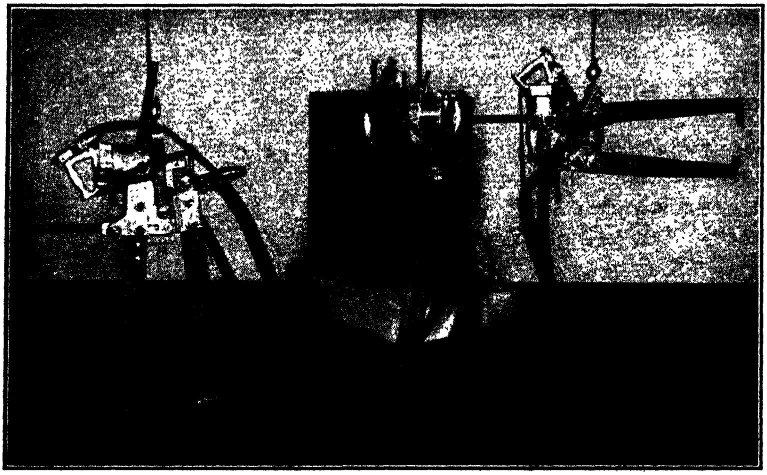
Spot welding is employed to join overlapping strips, sheets, or plates of metal at small areas. A spot-welding machine is illustrated in Fig. 102. The pieces are assembled and placed between two electrodes which are forced against the metal to be welded. For a limited amount of service, electrodes made of pure copper may be used, but, for continuous operation and heavy pressures, electrodes made of alloys of copper and tungsten, or copper and chromium, are most satisfactory. When the current is turned on, the pieces being welded are heated at their areas of contact to a welding temperature, and with the aid of mechanical pressure the metal is welded at a spot. Because of the close contact of the metal surfaces, there is no difficulty from oxidation of the metal in the weld, and fluxes are not required. The range of application of spot welding includes the joining of sheet steel and plate in all thicknesses up to $\frac{1}{2}$ inch.



Courtesy of Thomson-Gibb Electric Welder Company

FIG. 102—ELECTRIC RESISTANCE SPOT WELDER

Portable gun welders are a variation of the conventional spot welder. They are commonly used in progressive assembly line work and are especially adapted to fabricating bulky work or parts which are held in jigs. These welders have one or more portable, air-operated, pincer-type guns connected by flexible power and pressure leads to a cabinet containing the transformer, heat and air regulators, timing equipment, and the necessary connections. The cabinet is usually mounted on a truck or suspended from a traveling hoist or otherwise arranged so that it can be stationed at a point convenient to the work or moved about as conditions require. A portable welding gun can make welds in close quarters that could never be reached by a stationary spot welding machine. In Fig. 103 is shown a portable cabinet and three welding guns. The two larger guns have throat depths of 24 inches. Equipment of this kind is widely used in the fabrication of automobile bodies, steel cabinets, refrigerator cases, and similar products.

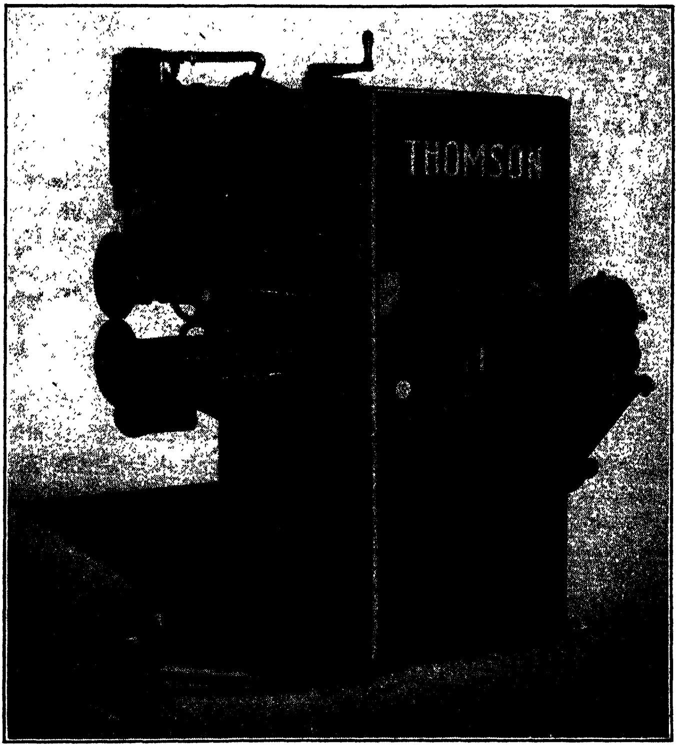


Courtesy of Thomson-Gibb Electric Welder Company

FIG. 103—PORTABLE GUN WELDERS

Projection welding is similar to spot welding in that the heat is confined to small ridges or bosses on the surfaces of the sheet steel which is to be joined. See Fig. 98. The flattening out of these projections under pressure results in good welds at all points of contact. The advantage of this method lies in the possibility of making a number of welds at one time between flat electrodes in a welding machine. Equipment for spot welding and projection welding is made in sizes which require ¼ to 250 kilowatts of electric power.

Seam welding is the method of making a continuous joint between two overlapping pieces of sheet metal. As in all electric resistance methods of welding, the heat is supplied by the resistance offered to the passage of a large electric current through the metals being welded. Two copper rollers or a copper roller on one side of the joint and a copper track on the other side serve as conductors for producing continuous welds. Pressure is applied to the rollers as they pass over the joint, and the overlapping surfaces of the metal are forced together as fast as they are heated to the welding temperature. In seam welding, the current is usually interrupted to control the heat, although in some applications the current is on continuously. A double-roll seam welder is illustrated in Fig. 104.



Courtesy of Thomson-Gibb Electric Welder Company

FIG. 104—ELECTRIC RESISTANCE SEAM WELDER

Resistance welding is employed in the manufacture of automobiles, electrical equipment, metal furniture, barrels, tools, and hardware. Although this process is particularly adapted to applications requiring large production, it is also used for jobbing and repair work.

"Thermit" Pressure Welding

Heat may be supplied for plastic welds by the "thermit" chemical reaction which will be described later in this chapter. The parts to be joined are heated by the products from the "thermit" reaction and mechanical pressure is applied to complete the weld. Among the applications of the plastic method of "thermit" welding is the welding of pipe. Special clamps are attached to the pieces of pipe to be welded and a mold is provided around the joint. The hot slag and superheated metal produced by the "thermit" reaction in a hand ladle are poured into the mold surrounding the surfaces to be welded. After the welding temperature is reached, the clamps are drawn up to force the ends of the pipe together, thus completing the weld. This method of welding may be employed to advantage in narrow trenches or when conditions are such that other welding methods can not be used.

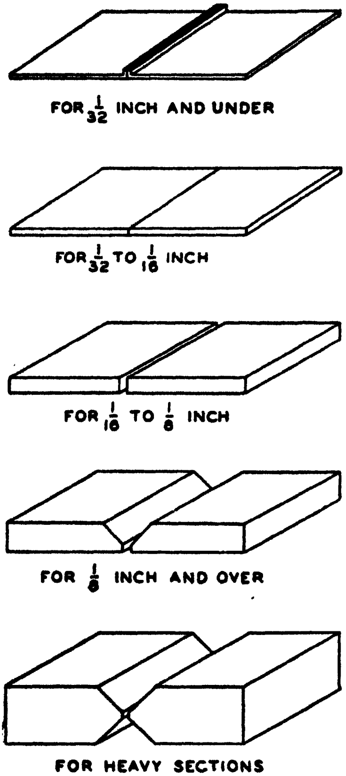
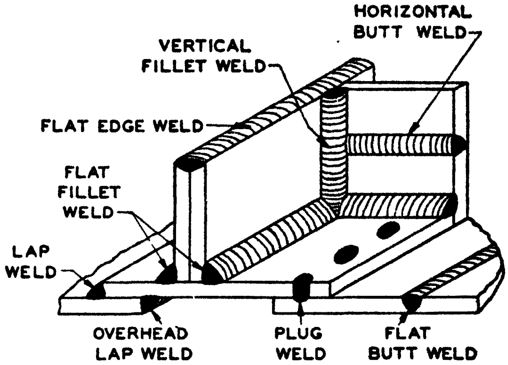


FIG. 105—METHODS OF PREPARING METAL SECTIONS FOR GAS AND ARC WELDING

FUSION WELDING PROCESSES

In the fusion welding processes, the metal surfaces to be joined, as well as the metal in the joint, are heated to the molten state so that the metal will flow together, and the weld be completed without the use of external pressure. These processes include gas welding, arc welding, and "thermit" welding. In the preparation of the metal for gas welding and arc welding, sections of $\frac{1}{8}$ inch and over are often beveled on the edges to permit thorough penetration and complete fusion of the metal in the weld. Some of the methods used in preparing steel of different thicknesses for welding are shown in Fig. 105. For very heavy sections, the joining groove is often made U-shape to allow access to the joint with a minimum addition of filler metal.

The designations of the types of fusion welds based on their locations are given in Fig. 106. A **flat weld** is a weld in a horizontal plane or a plane inclined at an angle of 45 degrees or less to the horizontal, the weld being made from the top side of the plane. An **overhead weld** is made from the under side of a horizontal plane or a plane inclined at an angle of 45 degrees or less to the horizontal. A **vertical weld** has its linear direction vertical or inclined at an angle less than 45 degrees to the vertical. A **horizontal weld** has its linear direction horizontal or inclined at an angle less than 45 degrees to the horizontal in planes which are either vertical or inclined less than 45 degrees to the vertical. Other designations for fusion welds are indicated on the drawing in Fig. 98. A **butt weld** is made between two pieces having their ends or edges squarely together. A **fillet weld** is made in the corner between pieces with surfaces intersecting at approximately right angles. **Lap welds** are made along the edges of two overlapping pieces. An **edge weld** is made across the ends of two pieces with their flat surfaces in contact. **Plug welds** are made in holes so as to join two pieces together at these areas. A **continuous weld** is one of unbroken continuity. On the other hand, an **intermittent weld** consists of a series of short beads placed at regular intervals. A **tack weld** is a temporary intermittent weld provided only to aid in assembling parts for additional welding.



Courtesy of Lincoln Electric Company

FIG. 106—TYPES OF WELDS

Gas Welding

Various gas combinations can be used for producing a hot flame for welding metals. Oxygen (O_2) and acetylene (C_2H_2) are in general use, although oxygen and hydrogen serve well for some purposes. These gases are thoroughly mixed in correct proportions in a torch and are burned at the tip.

Oxygen is the gas which supports combustion and is used in combination with fuel gases to develop heat. Most of the oxygen used commercially is obtained by compressing and cooling air until it becomes liquid and then allowing the nitrogen to evaporate separately. The remaining oxygen is compressed into seamless steel cylinders containing, when fully charged, 220 cubic feet of gas at a pressure of 2,000 pounds per square inch. The valve at the top of each cylinder (see Fig. 107) has a handwheel for opening or closing, and a threaded outlet connection to which an oxygen regulator or an oxygen manifold can be attached. The valve also contains a fuse plug that will melt or burst and thus release the contents of the cylinder when the temperature or pressure becomes excessive.

Acetylene is a combustible gas produced by bringing calcium carbide into contact with water. The calcium carbide is made by fusing lime and coke in an electric furnace. At pressures above 15 pounds per square inch, acetylene may explode under certain conditions. Therefore, free acetylene is never used at pressures higher than this. Lower pressures are adequate for welding and cutting operations. When large amounts of acetylene are needed, it is most economical to generate this gas in suitable equipment near the location where it is to be used. Where portability is a factor and wherever comparatively small quantities are required, acetylene is purchased in steel cylinders. These cylinders are completely filled with a highly porous material saturated with acetone, a liquid in which the acetylene gas is dissolved. Each cylinder when fully charged contains 300 cubic feet of acetylene.

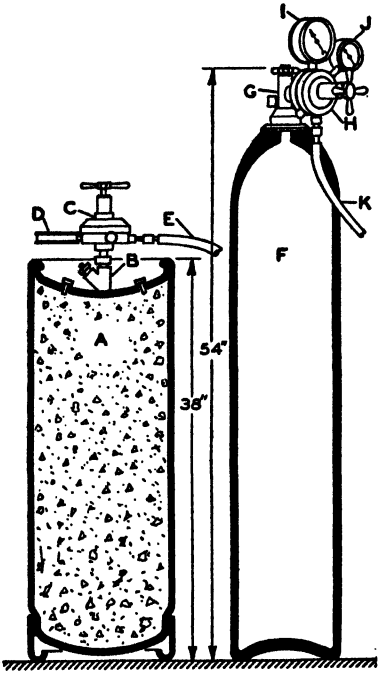


FIG. 107—CYLINDERS AND REGULATORS FOR OXY-ACETYLENE WELDING

A—Acetylene cylinder contains porous filler and acetone in which 300 cu.ft. of acetylene is dissolved.
B—Acetylene valve.
C—Acetylene regulator.
D—Cylinder presure gage, maximum 250 lb. per sq.in.
E—Hose to torch, pressure 4 to 6 lb. per sq.in.
F—Oxygen cylinder contains 220 cu.ft. of oxygen gas.
G—Oxygen valve.
H—Oxygen regulator.
I—Cylinder pressure gage, maximum 2000 lb. per sq.in.
J—Outlet pressure gage, 2 to 20 lb. per sq.in.
K—Hose to torch.

Safe Practices—Certain precautions should be observed in storing and handling oxygen and acetylene cylinders as well as in the use of the gases. All cylinders should be handled carefully and should be stored in well-protected, ventilated, and dry places. They should be kept away from heat, fire, molten metal, and electricity. They should be placed in an upright position where they will not fall or be knocked over.

Oxygen must be kept away from oil or grease. In the presence of oxygen under pressure, oil or grease will ignite violently. It is especially hazardous to handle oxygen valves or connections with greasy hands or gloves.

Acetylene forms explosive mixtures with air and oxygen, hence special care must be taken to prevent the formation of such explosive mixtures. The valve on an acetylene cylinder should be opened slowly. Acetylene gas should be taken from a cylinder only through a pressure-reducing regulator.

Equipment and Procedure for Gas Welding—The equipment required for oxy-acetylene welding includes cylinders containing oxygen and acetylene, a suitable hand torch, and rubber hose to connect the torch to the gas supply. Automatic regulators are used to reduce the pressures of the gases from those in the usual cylinders down to the pressures suitable for welding. A regulator maintains a constant pressure at the torch while the gas pressure in the cylinder is lowered continuously as the gas is consumed. The cylinders and regulators used for oxy-acetylene welding are shown in Fig. 107. Another essential part of the equipment for gas welding is the torch which is shown in Fig. 108. The desired proportions of the gases are adjusted by the valves on the torch, and these gases are thoroughly mixed before issuing from the tip. A number of interchangeable tips are provided with each torch so that flames of different sizes can be obtained. To increase the speed of welding during the construction of large pipe lines, special tips are used having as many as six flames; four flames preheat the walls of the pipe at the joint, one flame preheats the welding rod, and another flame does the actual welding. When oxygen and acetylene are supplied to the torch in nearly equal volumes, a neutral flame is produced having a maximum temperature of about 6300 degrees F. See Fig. 109. For

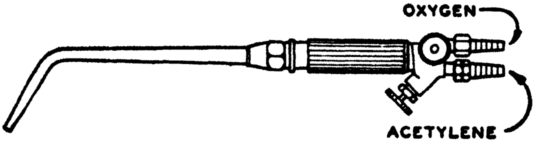


FIG. 108—WELDING TORCH

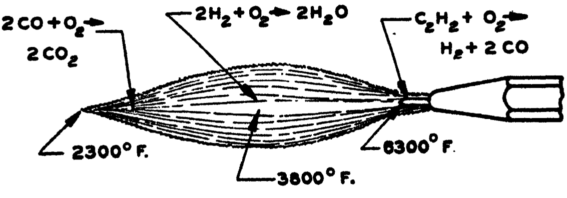

$2CO+O_2 \rightarrow 2CO_2$
$2H_2+O_2 \rightarrow 2H_2O$
$C_2H_2+O_2 \rightarrow H_2+2CO$
2300° F.
3800° F.
6300° F.

FIG. 109—OXY-ACETYLENE NEUTRAL WELDING FLAME

most gas welding, a neutral flame is desired, but in certain welding applications a slightly reducing or slightly oxidizing flame is needed. The condition of the flame can be readily determined by its appearance. The neutral flame has two definite zones, a sharp brilliant cone extending a short distance from the tip of the torch (see Fig. 109) and an outer cone or envelope only faintly luminous and of a bluish color. The outer envelope of the neutral flame protects the molten metal from oxidation because the oxygen in the surrounding atmosphere is consumed by the gases from the flame. See Fig. 110. As the proportion of acetylene in the gas mixture is increased, a reducing flame with a lower temperature is obtained. This flame has three zones: the sharply defined inner cone, an intermediate cone of whitish color, and the bluish outer envelope. The length of the intermediate cone is an indication of the proportion of excess acetylene in the flame. When oxygen is supplied in excess in the gas mixture, the inner cone of the flame is not sharply defined and has a purplish tinge.

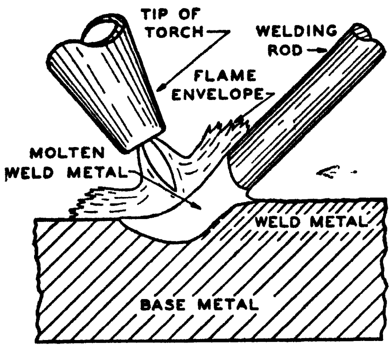


Fig. 110—Oxy-Acetylene Welding

Oxy-hydrogen welding was employed before oxy-acetylene welding was developed. For the welding of thin sheets of steel, the oxy-hydrogen flame having a temperature of 3600 degrees F. is preferred to the use of oxygen and acetylene.

Gas welding is accomplished by progressively melting the edges or surfaces to be joined and allowing the molten metal to flow together, thus forming a solid, continuous joint upon cooling. With material thicker than $\frac{1}{16}$ inch, additional metal is usually added to the weld in the form of welding rod which is melted into the welding puddle as it progresses along the joint. The composition of the welding rod is usually the same or nearly the same as that of the part being welded. To aid in the removal of impurities and to obtain a satisfactory bond, flux is employed during the welding of practically all metals except steel.

Two methods of manipulating the torch and rod are employed in gas welding. In one method known as forward welding, the torch is inclined with the tip pointing forward in the direction of welding, and the rod is held ahead of the flame (see Fig. 132 in the Appendix). With the flame and rod in these positions, the end of the rod prevents excessive melting of the material at the bottom of the crack. This is an advantage in welding light sections. In the other method, known as backhand welding (see Fig. 110), the torch tip is pointed backwards from the direction of welding, and the welding rod follows the torch as the metal is deposited. This procedure is particularly suited to the welding of thick sections because it permits thorough heating of the metal to the bottom of the joint.

Brazing—Steel parts are often joined by brass alloys containing approximately equal proportions of copper and zinc. The parts to be brazed are prepared with relatively close fits and are assembled before being heated. A gas flame is used to heat the metal to a temperature of about 1600 degrees F., at which the brass melts and flows into the joint. This procedure, known as **flame brazing**, requires the use of a flux (usually borax) to keep the surfaces clean and free from oxides. As the surfaces of the parts which are to be joined are not melted, a true fusion weld is not obtained. However, the combination of filler metal and base metal results in a brazed joint having considerable strength.

A process known as **copper brazing** is employed in the fabrication of metal products. In this process, the steel parts are assembled and copper wire is placed at the joints. The assemblies are then charged into a special furnace where they are heated gradually to 2100 degrees F. in an atmosphere of hydrogen gas. At this temperature the copper flows into the seams by the aid of capillary attraction. The hydrogen atmosphere prevents the formation of oxides on the steel, and, by producing clean surfaces, allows the copper to combine with the steel. The parts are cooled in the furnace and are later removed in a bright and clean condition.

Silver solders are ordinarily alloys of copper, zinc, and silver in which the proportion of the latter element may be 10 to 80 per cent of the total composition. The effects of silver are to lower the melting point of the alloys, to improve the flowing property, to promote soundness of the joint, and to increase the strength of the joints made with these solders. Some commercial alloys contain other elements such as phosphorus or cadmium to lower the melting point or to improve other properties of the brazing alloy. The melting points of silver solders range from 1200 degrees F. to 1600 degrees F. For some purposes, a solder having a low melting point must be used. To satisfy this requirement, an alloy containing 50 per cent silver, 15½ per cent copper, 16½ per zinc, and 18 per cent cadmium flows freely at 1200 degrees F. Another alloy employed extensively for brazing contains 80 per cent copper, 15 per cent silver, and 5 per cent phosphorus. This alloy melts about 1300 degrees F. and produces strong ductile joints. A silver solder which is used widely for brazing steel parts contains 50 per cent silver, 34 per cent copper, and 16 per cent zinc. This alloy flows at 1435 degrees F.

Silver solders are supplied in the form of filings, sheets, strips, and wire. Pieces of the solder are fitted between the parts to be joined or the solder is flowed into the joints after the parts are heated to the required temperature. A flux is used to prevent oxidation of the surfaces of the metals and to assist in the flowing of the solder. Borax or mixtures of borax and boric acid are usually satisfactory for this purpose. Although the cost of silver solders is relatively high, only a small amount is needed for each joint. Many operations, difficult if not impossible by other welding methods, can be done economically by silver soldering.

Oxygen Cutting—The cutting of steel with the aid of a gas torch is closely associated with gas welding, and because of its extensive use in the industries will be considered under this subject. When iron or steel is heated to a bright red color and is then exposed to a stream of commercially pure oxygen, the metal is oxidized rapidly with the development of sufficient heat to melt the resultant oxide. If the oxygen is supplied at a pressure which will blow away the molten oxide, a continuous cut can be made through the metal. A special torch shown in Fig. 111 is used when steel is cut with oxygen. The tip of this torch has four small openings surrounding a large opening at the center. When the cutting torch is being used, a mixture of acetylene (or other fuel gas) and oxygen is supplied through the small openings for preheating the metal to a temperature at which rapid oxidation takes place (about 1600 degrees F.). Then oxygen at a high pressure is supplied through the large opening for cutting the steel. The slag which is produced from the oxidation of the steel is blown off by the pressure of the gases.

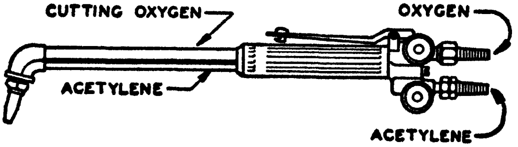


FIG. 111—CUTTING TORCH

Automatic machines are used extensively for the **flame cutting** of steel of practically any thickness. These machines have mechanical devices for guiding one or more cutting torches so that the pieces will be shaped to the desired outlines. With the proper adjustment of speed of travel and gas pressures, clean, sharp edges can be obtained on the material being cut to the desired shapes.

All carbon steels are readily oxidized, hence can be cut easily with a controlled stream of oxygen. However, some alloy steels contain chromium, nickel, and other elements in sufficient proportions to retard the oxidation of the metal. These materials are more difficult to cut with gas and are usually preheated throughout to temperatures up to 1000 degrees F. before being cut with the cutting torch.

An oxygen lance is used to cut large sections of steel or cast iron, or to make holes in large pieces of these metals. The lance consists of a long piece of $\frac{1}{8}$- or $\frac{1}{4}$-inch steel or iron pipe with a valve at one end connected to a supply of oxygen. A spot on the metal which is to be cut is heated to the kindling temperature with an oxy-acetylene torch. Then the end of the lance is brought against the heated area, and oxygen at a pressure of about 50 pounds per square inch is supplied through the pipe. The heated metal is oxidized rapidly and the molten oxide is blown away by the stream of gas. As the end of the pipe is gradually burned, the lance is fed into the cut or hole so that the supply of oxygen emerges in such a direction as to continue the cut or enlarge the hole.

Arc Welding

An electric arc is produced when two conductors of an electric current are brought together forming an electric circuit and then separated for a distance such that the current continues to flow through the gaseous medium between the solid conductors. Electrical energy is transformed at the arc into heat which is concentrated within a small space. The three methods of utilizing the heat of the electric arc for welding purposes are: (1) carbon-arc welding, (2) metallic-arc welding, and (3) atomic-hydrogen arc welding. In the first method, a rod of carbon is used as the negative electrode and the metal object being welded is positive. The arc produced between these electrodes heats the metal almost instantaneously to its melting temperature. A direct current is usually supplied for carbon-arc welding. When additional metal is required in the weld, it is introduced within the heating area of the arc.

In the second method, known as metallic-arc welding, a metal wire or rod is used as one electrode. During the welding operation, this metal electrode is melted by the heat of the arc and is fused with the base metal, thus forming a solid union after the metal has cooled. With this method of welding, an arc about $\frac{1}{8}$ inch in length is maintained by the operator. Metal can be deposited in practically all positions with the metal electrode.

The current required when carbon electrodes are used reaches at times 800 amperes, whereas the current supplied for metal-electrode welding rarely exceeds 600 amperes. The arc voltage which has been found to give satisfactory results in arc welding varies from 15 to 45 volts. A motor-driven, direct-current generator is commonly used for supplying the current for electric-arc welding. Other equipment, however, provides a single-phase alternating current taken from a transformer or supplied directly from a generator. Some welding units are designed to deliver alternating current at 240 cycles for arc welding.*

The conductor from which the direct current passes into the arc is designated as the positive terminal and the other conductor is the negative terminal. When the welding electrode is connected to the negative terminal and the work to the positive terminal, the circuit is known as "straight polarity"; when the connections to the source of power are reversed, the circuit is in "reversed polarity." The most satisfactory arrangement for the electrical connections depends upon the type of metal electrode and the operating conditions. Manufacturers of electrodes or rods for metallic-arc welding usually recommend the polarity to be used for each rod.

With manual operation in metal-electrode welding, the arc is "struck" by bringing the electrode in contact with the work for an instant and then withdrawing it a short distance so that the current continues to flow between the work and the electrode. Some skill is required in maintaining the correct length of arc and in feeding the electrode to the work as it is melted away by the heat of the arc. The most favorable welding conditions are judged by the cracking sound from the arc and by the appearance of the deposited metal. The types of beads produced under different operating conditions are illustrated in Fig. 112. The depth below the surface to which the fused zone extends is known as penetration. A favorable penetration of the fused metal is necessary to obtain strong welds.

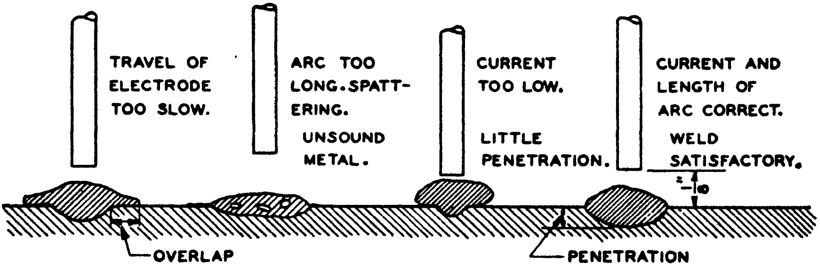

TRAVEL OF ELECTRODE TOO SLOW.
ARC TOO LONG. SPATTERING.
UNSOUND METAL.
CURRENT TOO LOW.
LITTLE PENETRATION.
CURRENT AND LENGTH OF ARC CORRECT.
WELD SATISFACTORY.
OVERLAP
PENETRATION

FIG. 112—CROSS SECTIONS OF BEADS DEPOSITED FROM METAL ELECTRODE

Weld metal is sometimes hammered or peened to reduce the total contraction of the metal during cooling. Peening thus controls the distortion or change in dimensions of the part due to welding. If the peening is done while the metal is at a red heat, the grain size of the weld metal will be reduced. On the other hand, cold working of the weld metal produces a brittle condition. Another method of refining the grain and thereby raising the ductility of steel welds is to use several smaller beads rather than making a single pass to fill the weld groove. In this way, the metal in the first bead is refined by the heat from the second bead. The metal in the second bead is also refined by the heat from the third bead, and so on.

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* The specific power requirements as to voltage and current for a definite arc-welding project depend upon the size and type of electrodes as well as the nature of the work. As a rule, each operator regulates his equipment to obtain the results desired.

Metal electrodes are available of compositions suitable for welding all types of constructional steels, as well as for welding aluminum and copper alloys. Electrodes of special composition are also employed for building up edges on tools and for producing wear-resisting surfaces on machine parts. The specifications of the *American Welding Society* include the following analyses of welding electrodes:

Specification E No. 1 A

Carbon	not over 0.06 per cent
Manganese	not over 0.15 per cent
Silicon	not over 0.08 per cent
Sulphur	not over 0.04 per cent
Phosphorus	not over 0.04 per cent

For welding structural steel shapes, plates, bars, low-carbon steel forgings and castings.

Specification E No. 1 B

Carbon	0.13 to 0.18 per cent
Manganese	0.40 to 0.60 per cent
Silicon	not over 0.06 per cent
Sulphur	not over 0.04 per cent
Phosphorus	not over 0.04 per cent

For welding structural steel shapes, plates, bars, low-carbon steel forgings and castings.

Specification E No. 1 C

Carbon	0.85 to 1.10 per cent
Manganese	0.30 to 0.60 per cent
Silicon	not over 0.06 per cent
Sulphur	not over 0.04 per cent
Phosphorus	not over 0.04 per cent

For welding high-carbon steel and worn surfaces where great resistance to abrasive wear is desired and where machining is not necessary.

An examination of the metal in an arc weld made with a bare metal electrode reveals some non-metallic inclusions which decrease the strength and ductility of the weld. As the globules of metal pass from the electrode to the work, they are exposed to the oxygen and nitrogen in the surrounding air. See Fig. 113. This causes the formation of some non-metallic constituents which are trapped in the rapidly solidifying weld metal. With the purpose of decreasing the contamination of the metal in the weld, metal electrodes are usually coated with materials which burn and form a non-oxidizing atmosphere around the weld. Furthermore, a slag is produced from the coating material which protects the weld metal from oxidation. The diagram in Fig. 114 shows how the metal in the weld is protected or shielded when a coated electrode is used. Welds made with a shielded arc have superior physical qualities to those made with bare metal electrodes.

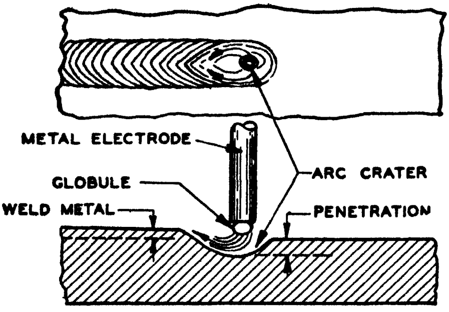


Fig. 113—Diagram of Welding Arc with Bare Electrode

Arc welding can be accomplished either by manual operation or by automatic machines in which the travel of the arc and feeding of the welding wire are controlled mechanically. For manual operation, the electrodes are gripped in holders as shown in Figs. 115 and 116. Metal electrodes are supplied in sizes from $\frac{1}{16}$ to $\frac{3}{8}$ inch in diameter and in lengths of 14 and 18 inches. Carbon electrodes can be obtained in sizes $\frac{3}{16}$ to $\frac{1}{2}$ inch in diameter and in lengths of 12 inches.

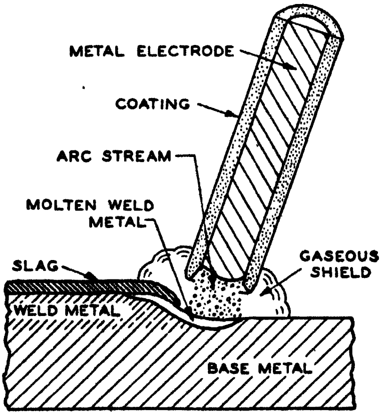


Fig. 114—Shielded Arc

Because of the intensity of the heat and light rays from the electric arc, the operator's hands, face, and eyes are protected while the arc is in use. Heavy gloves are worn, and a hand shield or a helmet with window of colored glass serves to protect the operator's face. It is important also to safeguard other workmen from the glare of the arc; hence the space for electric welding is usually screened off from the rest of the building.

The third method for using the electric arc in welding is designated as **atomic-hydrogen arc welding.** In this process, a single-phase, alternating-current arc is maintained between two tungsten electrodes, and hydrogen gas is introduced into the arc from openings around the electrodes. As the molecules of hydrogen pass through the electric arc, they are changed to the atomic state; and when the atoms of hydrogen recombine into molecules just outside the arc, a large amount of heat is liberated. This heat is used in making fusion welds. When additional metal is required, filler rods are melted into the joints. The presence of an atmosphere of hydrogen around the welds prevents the oxidation of the tungsten electrodes as well as of the weld metal.

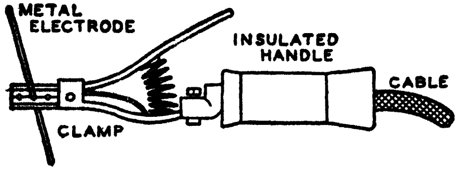


FIG. 115—METAL-ELECTRODE HOLDER

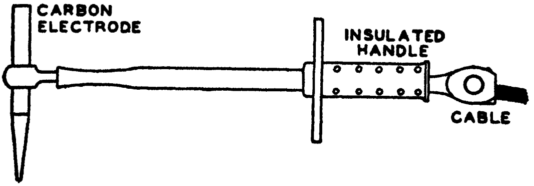


FIG. 116—CARBON-ELECTRODE HOLDER

The equipment required for this process consists of a control panel on which the electrical instruments are mounted, a transformer for changing the voltage of the electrical supply to the voltage required for welding, an electrode holder for regulating the arc, and connections to tanks of hydrogen. The electrode holder shown in Fig. 117, which was developed by the General Electric Company, has an insulated handle with two electrode clamps, one of which is movable by means of a lever. Openings are provided in the electrode clamps, through which the hydrogen flows to the arc. The cable which carries the current for the electrodes and the tube for hydrogen gas pass through the handle of the electrode holder.

When the atomic-hydrogen arc welding apparatus is in operation, the maximum voltage at the electrodes ranges from 60 to 90 volts. An electric current of 35 amperes is used in welding with $\frac{1}{16}$-inch tungsten electrodes. Hydrogen gas is supplied to the arc at a pressure of 6 to 8 lb. per sq. in. The length of the arc, which is adjusted by the lever on the electrode holder, is maintained so that at all times the distance between the electrodes is about $\frac{1}{4}$ inch. During the welding operation, the ends of the electrodes are held about $\frac{1}{2}$ inch from the metal being welded.

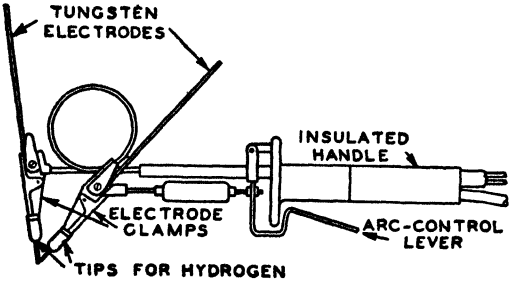


FIG. 117—ELECTRODE HOLDER FOR ATOMIC-HYDROGEN ARC WELDING

The atomic-hydrogen welding process can be used to advantage for welding many special alloys such as high-chromium and high-nickel steels. Some of the applications of this process are the welding of boiler shells, the fabrication of thin sheet-steel parts, and the repair of dies. Strong and ductile welds free from porosity can be obtained by the atomic-hydrogen process.

"Thermit" Welding

The "thermit" process for welding steel is based on the chemical reaction between finely divided aluminum and iron oxide:

$$8Al + 3Fe_3O_4 \rightarrow 4Al_2O_3 + 9Fe$$

When this reaction is started with the aid of external heat, the aluminum combines with the oxygen of the iron oxide to form aluminum oxide (slag), and molten iron is set free in a highly superheated state.

Plain "thermit" is a mixture of granulated aluminum and iron oxide, the ratio by weight being approximately three parts of iron oxide to one part of aluminum. To obtain the desired composition in the weld metal, alloys are added to the "thermit" materials. The usual mixture for welding steel consists of 1 pound of nickel shot, 1 pound of crushed ferromanganese, 20 pounds of steel punchings, and 100 pounds of plain "thermit." The temperature produced by the "thermit" reaction is approximately 5000 degrees F., or about twice the temperature of the melting point of steel. The "thermit" mixture is not explosive; hence there is no danger in handling or storing the materials. The high temperature which is required to start the "thermit" reaction is obtained by burning a small amount of magnesium powder.

In making welds by the "thermit" process, the parts to be united or built up are partially imbedded in a sand mold, and the metal exposed within the mold is first heated by the flame from a torch. Then the "thermit" reaction is started in the crucible, and the superheated metal is run into the mold.

In the preparation of the parts to be welded, an opening is cut away between the pieces which are to be joined, the amount of the opening depending on the size of the sections. Then the ends of the pieces are thoroughly cleaned on each side of the fracture. When the pieces are being mounted for welding, it is necessary to allow for the contraction of the metal as it cools from the molten state.

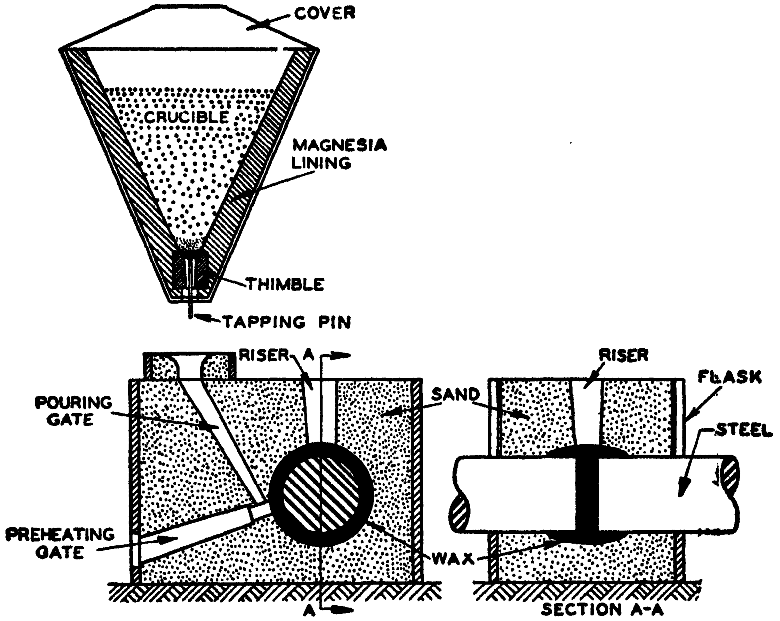


FIG. 118—EQUIPMENT AND MOLD FOR "THERMIT" WELD

A pattern of wax is shaped around the parts to be welded as shown in Fig. 118. The opening between the metal surfaces is also filled with wax. A metal box is then placed around the parts to be welded, and a refractory mixture of quartz sand and fire clay is rammed uniformly around the wax pattern. A pouring gate, riser, and preheating gate are provided in the mold as shown in Fig. 118. When the mold is completed, heat is applied with a torch at the lower opening to burn out the wax and to preheat the exposed metal parts. Then the burner is removed, and the preheating gate is plugged with sand.

While the preheating is in progress, a charge of "thermit" is placed in the conical-shaped crucible which is supported above the pouring gate of the mold. The amount of "thermit" required is dependent upon the volume of metal required in the weld. This can be established by using "thermit" in the ratio of twenty-five times the weight of the wax used in making the pattern. A small quantity of magnesium powder is placed on the "thermit" mixture in the crucible, and this is ignited by a match or a hot iron. Within one minute, the "thermit" reaction is complete and the slag (Al_2O_3) has risen above the metal in the crucible. Then the metal is allowed to flow into the mold by striking the pin at the bottom of the crucible. The highly superheated metal melts the ends of the parts being joined, and finally the whole solidifies into one mass. The welded section is allowed to cool slowly in the mold. Later the gates, riser, and all extraneous metal are removed from the joint.

The "thermit" process of welding is particularly adapted to the repair of heavy sections of cast iron or steel where large quantities of weld metal are required. These applications include the repair of large machine parts, railroad equipment, parts of ships, and steel-mill equipment.

Hard Facing

The process of hard facing involves welding a layer of wear-resisting alloy to those surfaces of tools or machine parts which are subjected to severe abrasive wear. This process is used not only for the repair or salvaging of worn parts but also during the manufacture of new equipment. By providing extra protection to the wearing surfaces of tools and machinery, the service life of this equipment can be lengthened considerably. Fewer replacements with the resultant savings in labor charges and lost production time will result from this practice.

A number of hard-facing alloys have been developed with widely different compositions. In general, these materials may be classified into five groups as follows:

Group 1—Cast iron and high-carbon steel. These alloys are usually somewhat brittle but under some circumstances may be satisfactory.

Group 2—Alloy steels containing varying amounts of chromium, tungsten, manganese, silicon, and carbon; the total of all alloying elements including carbon being less than 20 per cent. These are essentially austenitic alloys which are most serviceable for hard facing parts subjected to severe impact. They are also used as a filler in building up worn parts preparatory to applying a harder alloy on the wearing surface.

Group 3—In this group are the iron-base alloys containing more than 20 per cent and as much as 50 per cent of one or more of the elements chromium, tungsten, cobalt, nickel, manganese, silicon, and carbon. These hard-facing metals are necessarily higher in price than those with a lower alloy content in Group 2. However, they are harder, possess greater abrasive resistance, and give longer service.

Group 4—Alloys of cobalt, chromium, and tungsten which are available in different grades, all highly resistant to abrasive wear, but differing in strength and toughness. The particular advantage of these alloys lies in their ability to retain hardness at high temperatures. These alloys are cast in the shape of rods. Although the cost of these hard-facing alloys is relatively high, their superior wear resistance warrants their use on many tools and machine parts.

Group 5—This group contains tungsten carbide in different forms, which is the most wear resistant of all hard-facing materials. The tungsten carbide is usually bonded with cobalt or nickel to obtain toughness. Small inserts of tungsten carbide are imbedded by welding in the surfaces of parts which are hard faced. An important application of this material is hard facing for oil-well drilling tools. Tungsten carbide is also produced in a granular form which is packed in steel tubes or fused to strips of steel to be applied like ordinary welding rods.

The iron-base alloys used in hard facings (Group 1, 2, and 3) are ordinarily supplied in the form of welding rods for use in the electric arc or gas welding processes. For the nonferrous alloys (Group 4 and 5), the oxy-acetylene method is usually recommended. The selection of the most suitable hard-facing material for any application should be made only after considering all the conditions under which the wearing part is to be used.

REVIEW QUESTIONS

1. What precautions are taken to assist in obtaining sound forge welds?
2. Show on a sketch the essential parts of an electric resistance spot welder.
3. What are the advantages of electric resistance welding over other welding processes?
4. Describe the equipment required for oxy-acetylene welding.
5. What reaction is involved in the cutting of steel with the gas torch?
6. Describe three methods for utilizing the heat of the electric arc for welding purposes.
7. Explain the advantages of using coated metal electrodes in arc welding.
8. State three purposes of the hydrogen gas in the atomic-hydrogen arc welding process.
9. What heat-producing reaction is employed in "thermit" welding?
10. Discuss the different types of hard-facing materials.

CHAPTER XII

THE PRESERVATION OF STEEL

THE APPLICATION OF NON-METALLIC FILM COATINGS—THE APPLICATION OF METALLIC COATINGS—THE FORMATION OF CORROSION-RESISTING COMPOUNDS

Corrosion is the slow oxidation and consequent wasting away of metals, usually at ordinary temperatures. It is well known that iron corrodes in a moist atmosphere with the formation of rust or iron oxide on the exposed surfaces. The iron alloys can be protected from oxidation by coatings which are inert or resistant to corrosion.

Owing to the ever-increasing uses of iron in various commercial forms, the preservation of iron and steel is continuously becoming of greater economic importance. It has been estimated that several hundred thousand tons of steel are required each year in the United States to replace that which is destroyed by rust. Such enormous waste warrants the attention of steel users to the adoption of suitable rust-preventive measures. The corrosion problem has become more serious with advances in civilization, because the waste gases from the combustion of fuel, and stray electric currents from high-potential circuits, aid in the destruction of the metals.

As corrosion is the result of an oxidizing reaction, the presence of oxygen or air is necessary in promoting the formation of rust. But iron or steel does not oxidize at ordinary temperatures in dry air. This change in composition takes place only in the presence of moisture. Therefore, the metals can be protected from atmospheric corrosion by mechanically excluding air and moisture.

Some metals are more readily corroded than others. Zinc has a greater tendency to become oxidized than iron, hence a coating of zinc offers good protection to articles made of steel. On the other hand, iron is more rapidly attached than copper, and a copper coating will be effective only as long as the iron is completely covered.

The successful application of protective coatings requires that the metal surfaces be free from rust, detachable mill scale, dirt, and grease. Steel parts can be cleaned by immersion in acidic or alkaline solutions.

Gasoline and other organic solvents are often used in removing oil from steel parts after machining operations. Of the mechanical methods for cleaning, the sand blast or shot blast is generally used. A stream of high-pressure air into which sand or other abrasive is introduced is directed upon the pieces being cleaned. Another method of mechanical cleaning requires tumbling the steel parts in a rotating barrel with or without the presence of abrasive materials.

Paint is sometimes applied directly over the scale which is formed during the rolling process in the manufacture of structural steel. As long as this layer of scale remains intact, it serves as a protection to the metal underneath. In the same way, the surfaces of iron and steel castings resist corrosion better before machining than after the outside skin has been removed.

Many processes have been developed for preserving iron and steel from the destructive effects of corrosion. The protective methods in general use may be classified into three main groups: (1) the application of non-metallic film coatings including oils, paints, and enamels; (2) the application of metallic coatings such as zinc and tin; (3) the formation of coatings in which the iron to be protected is itself converted at the surface into a less corrodible compound. The outline which follows includes the different methods used in protecting iron and steel against corrosion.

1. The application of protective film coatings by:
    - (*a*) Oiling or greasing the surfaces.
    - (*b*) Painting by spraying, dipping, or brushing.
    - (*c*) Baking coatings in ovens at 300 to 500 degrees F. (japanning).
    - (*d*) Melting a glass-like material on the surfaces at 1500 degrees F. (vitreous enameling).

2. The application of metallic coatings by:
    - (*a*) Dipping in solutions of salts of the metals.
    - (*b*) Electroplating with nickel, copper, zinc, or other metals.
    - (*c*) Spraying molten metals (Schoop process).
    - (*d*) Dipping in molten zinc at 850 degrees F. (hot galvanizing).
    - (*e*) Dipping in molten tin at 500 to 550 degrees F. (tinning).
    - (*f*) Dipping in molten lead or lead-tin alloys at 700 degrees F. (lead coating).
    - (*g*) Dipping in molten lead-tin-antimony alloy at 640 degrees F. (Lohmann process).
    - (*h*) Contact with zinc dust in retorts at 700 degrees F. ("sherardizing").

- (*i*) Contact with aluminum and aluminum oxide in a reducing atmosphere at 1500 degrees F. ("calorizing").
- (*j*) Contact with chromium dust and aluminum oxide in a hydrogen atmosphere at 2400 degrees F. ("chromizing").
- (*k*) Contact with silicon carbide in chlorine atmosphere at 1750 degrees F. ("siliconizing").
- (*l*) Cladding sheet steel with stainless steel or nickel.

3. The formation of a more non-corrosive compound at the surface of the metal by:
    - (*a*) Heating to definite temperatures in a furnace or in a molten, oxidizing, salt bath at 500 to 800 degrees F. (temper coloring or niter bluing).
    - (*b*) The application of chemical reagents to oxidize the metal (Browning process).
    - (*c*) Heating in the presence of a volatilized oil or a smoky atmosphere at 420 degrees F. ("carbonia" process for gunmetal finish).
    - (*d*) Heating in an alkaline, oxidizing solution at 212 degrees F. (Guerini process).
    - (*e*) The application of phosphoric acid in alcohol solution ("deoxidine" process).
    - (*f*) Heating in a solution of phosphates and phosphoric acid at 212 degrees F. (Coslett process and Parker process).

Some of these processes are protected by patents, and rights to use such processes should be obtained from the holders of the patents. Unless otherwise stated, the processes are operated at room temperature.

THE APPLICATION OF NON-METALLIC FILM COATINGS

The use of oil or grease produces a temporary protection to steel parts by preventing air and moisture from coming in contact with the metal. A material which serves well for this purpose is the residue remaining in the stills after the distillation of the lighter products from crude oil. Mixtures of oils having the consistency of paint and known as slushing oils are used for coating finished surfaces of machines when they are stored or shipped.

The application of a protective film of paint is perhaps the most generally used method for preserving metals from oxidation. Paint is usually prepared from a pigment or base material, a drying oil such as linseed oil, a metallic oxide drier which hastens the oxidation (hardening) of the oil, and a thinner such as turpentine. The priming or first coat should contain an inert or inhibiting pigment such as lead oxide, lead chromate, zinc oxide, or zinc chromate. Some pigments such as lampblack, graphite, and barytes tend to stimulate corrosion and should not be used in first coats on metal surfaces. A paint film is not entirely impervious to moisture, but if carefully applied and composed of suitable materials will retard corrosion for long periods.

Lacquers consist of a resin or resin-like material dissolved in a volatile solvent. Pigments may also be added to color the lacquer. After the lacquer has been applied to the surfaces of the metal (by spraying, dipping, or brushing), the solvent evaporates leaving a thin film of the dissolved material which is quite impervious to moisture. When lacquers are baked after drying, the surfaces so coated are said to be japanned. A black japan is prepared by melting hard asphalt in hot linseed oil and adding a thinner such as naphtha. When the surfaces of metal parts are coated with the japan and are heated, the naphtha evaporates, the asphalt melts, and the linseed oil oxidizes, producing a hard glossy finish. The baking temperatures generally range from 300 to 500 degrees F.

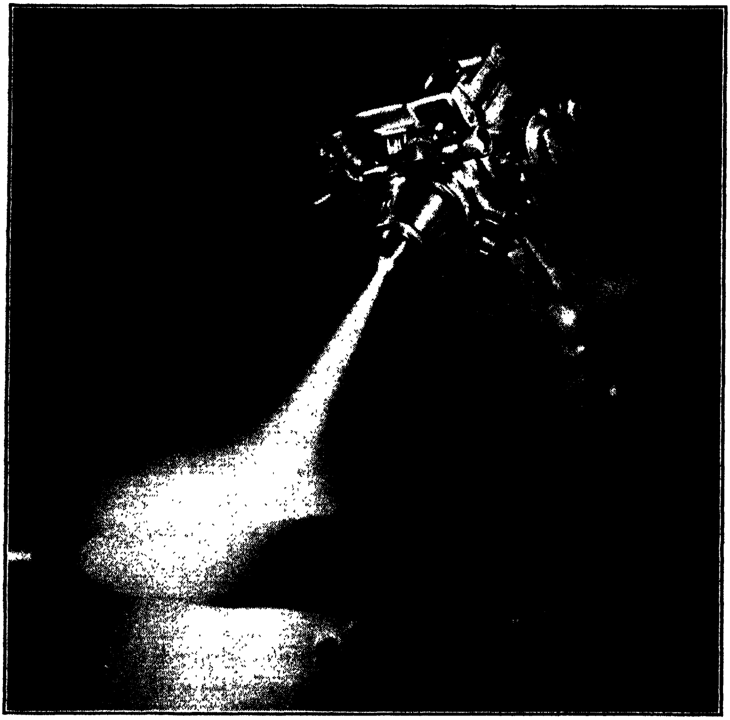
Enameling is a process for producing a smooth vitreous coating on metals. Mixtures of various materials which generally include finely ground silica, feldspar, and borax are applied by dipping or spraying. Following these operations, the enameled material is heated for short periods in ovens at about 1500 degrees F. to melt the enamel coating so that a hard smooth surface layer will remain after cooling.

THE APPLICATION OF METALLIC COATINGS

Protective coatings which are less readily oxidized than iron can be obtained by immersing the metal parts in solutions of the salts of certain metals. Steel pins are tinned by being immersed in a hot solution of tin chloride. Some of the iron goes into solution and is replaced by a thin layer of tin.

Electroplating is the process in which metals are deposited with the aid of an electric current. The objects to be coated are attached to the negative electrode; the metal to be deposited serves as the positive electrode; and a solution of a soluble salt of this metal is used as the electrolyte. As metal parts can be electroplated without destroying the properties produced by previous heat treatments, a protective coating of nickel, zinc, or chromium can be used to advantage on heat-treated parts. Chromium plating is employed not only to prevent corrosion, but also because of its resistance to abrasion.

The Schoop process consists of spraying molten metal on the surfaces of objects which require protection from corrosion. Zinc in the form of a wire is fed into a spray gun where an oxyacetylene flame melts it, and a strong current of air projects it from the nozzle as a fine spray. Coats of other metals such as tin, lead, aluminum, copper, and steel are also deposited in this way. Moreover, a homogeneous coating of any thickness can be produced by metal spraying. The nozzle of the spray gun shown in Fig. 119 has three concentric tubes. The wire is advanced through the central tube by an air-operated motor, the gaseous mixture of acetylene and oxygen passes through the annular space surrounding the central tube, and the compressed air which accomplishes the atomizing and spraying passes through the outermost annular space.



Courtesy of Metallizing Company of America

FIG. 119—METAL SPRAY GUN IN OPERATION

The easily fusible metals such as zinc, tin, lead, and their alloys are used as coatings for other metals. They are applied by dipping the articles to be coated in the molten metal, and removing the excess metal from the pieces by the action of centrifugal force or by rubbing.

A process which is widely used for producing a protective coating of zinc on iron and steel is hot-dip galvanizing, in which the metal is first coated with a flux and then dipped in molten zinc. After the metal to be coated has reached the temperature of the zinc bath, it is removed, and the excess zinc is thrown off in a centrifugal machine or is wiped off. Hardware of all kinds, sheet steel, and wire are coated with zinc by hot-dip galvanizing.

In tin plating sheet steel by the hot-dipping process, the sheet is passed through molten flux into the bath of molten tin and out through a layer of palm oil where the excess tin is wiped off. In passing through the palm oil, the tin coating is cooled without being oxidized.

The Lohmann process is used for coating iron and steel sheets with a protective alloy of lead, tin, and zinc. The metal is first dipped in a solution of hydrochloric acid, mercuric chloride, and ammonium chloride. In this solution, the surfaces become amalgamated with mercury, which prevents oxidation. The sheets are then dried and immersed in the molten alloy.

"Sherardizing" is a process for producing a zinc coating on small steel parts. The articles after being cleaned are placed in a cylindrical drum together with finely powdered zinc. After closing the metal drum, the contents are heated to 700 degrees F. for about 3 hours. The zinc is vaporized at this temperature and combines with the steel, forming a layer which is highly resistant to corrosion. The cylinder is rotated slowly to insure a uniform coating on the steel parts.

In the "calorizing" process, the articles to be treated are placed in a stationary or rotary retort with a mixture composed of finely divided aluminum and aluminum oxide. A reducing atmosphere is maintained in the retort, and the entire contents are heated to temperatures of 1100 to 2000 degrees F. The aluminum combines with the exposed portions of the metal parts to form a homogeneous aluminum alloy of any desired depth. "Calorized" metals are particularly adapted to resisting oxidation at high temperatures, and are therefore used in carburizing and annealing boxes, pyrometer tubes, and furnace castings.

Chromium impregnation or "chromizing" is a process of forming a high-chromium corrosion resistant case on low-carbon steel. The articles to be chromized are packed with chromium dust and aluminum oxide in a retort and heated to about 2400 degrees F. in a hydrogen atmosphere for 3 to 5 hours. The chromium diffuses into the steel to a depth of 0.01 to 0.02 inch. This diffused layer may contain as much as 20 per cent chromium alloyed with the iron.

Silicon impregnation or "siliconizing" is a process of forming a high-silicon case on low- or medium-carbon low-sulphur steel parts to improve the corrosion resistance toward acids and corrosive vapors. The parts to be siliconized are packed with silicon carbide in a retort and are heated to about 1750 degrees F. Chlorine gas is then admitted to the retort. After holding at the temperature for 2 hours, a case 0.025 to 0.030 inch in thickness with approximately 14 per cent silicon will be produced. Following this treatment, the steel may be heat treated to develop any desired structure.

Clad sheet steel has a layer of stainless steel or nickel 5 to 20 per cent of the thickness of the sheet bonded to one or both sides. In cladding with stainless steel, two sheets of stainless steel separated by a lacquer coating are welded together around their edges and placed vertically in an ingot mold to divide it into two rectangular parts. Low- or medium-carbon steel is poured on each side of the stainless steel sheets. The ingot is then hot rolled to the required thickness, and the plate is split, producing two sheets of stainless clad steel. Nickel or nickel alloy clad steel is manufactured by pressure welding the cladding metal to a steel slab in a rolling mill at about 2200 degrees F. The slab is then hot rolled to the required thickness. Clad sheet steel is cheaper than stainless steel or nickel of the same strength requirements, and is used in contact with corrosive liquids or gases to which the cladding metal is resistant.

THE FORMATION OF CORROSION-RESISTING COMPOUNDS

The formation of a uniform coating of magnetic oxide (Fe_3O_4) on the surface of steel parts renders the metal fairly resistant to corrosion. One of the simplest ways of producing this oxide coating is to heat pieces of steel in an open furnace or in a fused salt bath at temperatures of 500 to 800 degrees F. A mixture of sodium and potassium nitrates is sometimes used to produce a coating having a dark blue color. The pieces of metal are immersed in the fused salts for a few minutes and are then quenched in water.

The Bower-Barff process for producing a film of oxide on iron and steel parts consists of heating the articles in a closed retort to a temperature of 1600 degrees F. Superheated steam is then introduced into the retort, and, after a coating of ferric oxide (Fe_2O_3) has formed on the metal surfaces, producer gas or mineral oil is supplied to reduce this oxide to the more resistant form of Fe_3O_4.

The Browning process is used largely for producing special finishes on gun parts. Various combinations of chemical reagents are used to oxidize the steel. The loose rust is then scraped off, leaving an adherent layer of oxide. This treatment is repeated a number of times, and finally the surface is oiled.

In the "carbonia" process, the steel is heated in contact with charred bone and oil. A black oxide coating which offers a fair degree of resistance to corrosion is thus formed on the surfaces of the steel parts. This process produces a gunmetal finish.

When steel is treated in boiling alkaline oxidizing solutions, a noncorrosive coating is produced on the metal. The Guerini process uses a sodium hydroxide solution containing sodium picrate.

The "deoxidine" process is used for rust-proofing steel preparatory to painting. This process consists of rubbing the metal surfaces with a solution of phosphoric acid in alcohol and water, and then washing off the "deoxidine" solution with water. After the surfaces have dried, they are ready to receive a coating of paint or enamel. This treatment prevents corrosion of the metal underneath the paint film.

Rust-proofing by the Coslett process is effected by immersion of the clean objects in a hot solution of iron phosphate and phosphoric acid. After remaining in this solution for a short time, the steel becomes coated with a rust-resisting deposit of iron phosphate.

The Parker process uses a dilute solution of manganese dihydrogen phosphate. The iron or steel articles to be processed are immersed in this solution which is kept at 210 degrees F. An insoluble phosphate coating is formed on the metal surfaces in a period of 40 to 90 minutes. The articles are then rinsed in boiling water, stained black, and oiled. Paint or lacquer is sometimes applied over Parkerized surfaces.

REVIEW QUESTIONS

1. What conditions are necessary to promote the corrosion of steel?
2. Classify the methods for resisting corrosion into three main groups.
3. Outline the processes which can be used in applying metallic coatings to steel parts.
4. What are the constituents in a baking japan?
5. What methods are used in producing a zinc coating on steel?
6. State the advantages of chromium as a protective coating on steel?
7. Explain the "sherardizing" process for corrosion prevention.
8. What is the particular application of "calorized" steel?
9. Explain the procedure used in the Bower-Barff process.
10. Describe the Parker process for protecting steel from corrosion.

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LABORATORY ASSIGNMENTS

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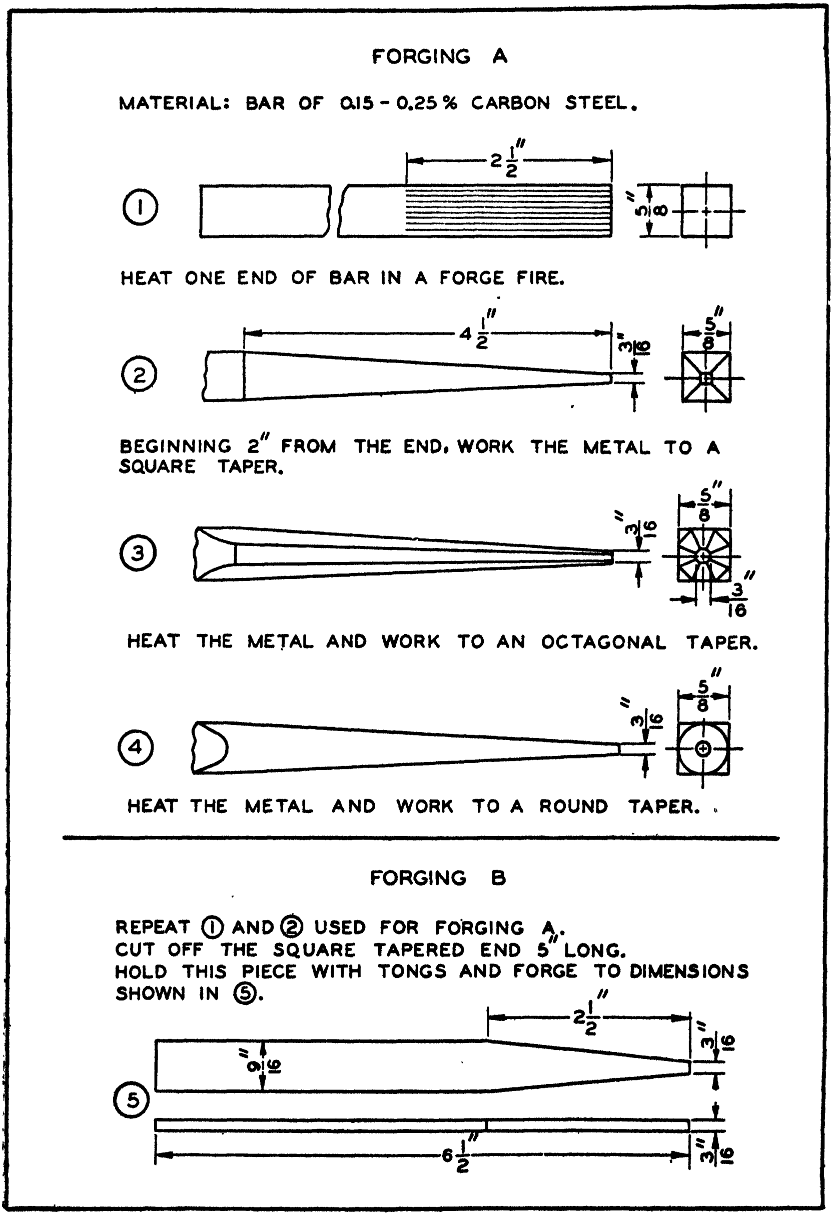


FORGING A

MATERIAL: BAR OF 0.15 - 0.25 % CARBON STEEL.

HEAT ONE END OF BAR IN A FORGE FIRE.

BEGINNING 2" FROM THE END, WORK THE METAL TO A SQUARE TAPER.

HEAT THE METAL AND WORK TO AN OCTAGONAL TAPER.

HEAT THE METAL AND WORK TO A ROUND TAPER.

FORGING B

REPEAT ① AND ② USED FOR FORGING A.
CUT OFF THE SQUARE TAPERED END 5" LONG.
HOLD THIS PIECE WITH TONGS AND FORGE TO DIMENSIONS SHOWN IN ⑤.

Fig. 120—Forgings Made by Drawing-Out Operation

LABORATORY ASSIGNMENT 1

USE OF THE FORGE AND SOME FORGING OPERATIONS

Object: To obtain correct heating conditions and temperatures in a forge fire, and to observe the plasticity of steel at different temperatures. Practice in hot working steel by the drawing-out operation.

Material: One bar of $\frac{5}{8}$-inch square carbon steel containing 0.15 to 0.25 per cent carbon (*S.A.E.* 1020).

Procedure: *Forging A.*—Heat one end of the bar of steel in a forge fire to about 2300 degrees F (white heat), and draw out the metal to a square taper as shown in Fig. 120. Heat the metal again to about 1800 degrees F. (bright yellow color), and forge the corners of the tapered end of the bar first to an octagonal shape and then to a round taper as shown in Fig. 120.

Forging B.—Repeat the first two steps used in making Forging *A* and cut-off on the hardie the square tapered end 5 inches long while the metal is at a temperature of about 1500 degrees F. Hold the small end of the tapered piece with tongs, heat to 2000 degrees F., and draw out the steel to the dimensions given in Fig. 120.

Notes: Heat is produced in a forge fire by the combination of oxygen from the air blast with the carbon of the fuel. If more oxygen is introduced into the fuel bed than is consumed by the coke in the time allowed for combustion, the excess oxygen will attack the iron or steel which is being heated and form a scale of iron oxide on the surface of the metal. In order to prevent the formation of a large amount of scale on the work, it is necessary to keep a thick layer of coke above and below the metal being heated in the forge fire.

The plasticity of steel increases as the temperature of the metal is raised. When a large amount of deformation is necessary in making a forging, relatively high temperatures (2000 to 2400 degrees F.) are used so as to complete the working of the metal with as few heats as possible. These high temperatures result in a coarsening of the grain structure of the metal. Therefore, it is important that the metal be worked soon after the forging temperature has been obtained and that the hot working be continued until the temperature has lowered to about 1550 degrees F. Hot working produces small grains in steel which has been thoroughly worked to the correct finishing temperature.

Reference: Chapter VI.

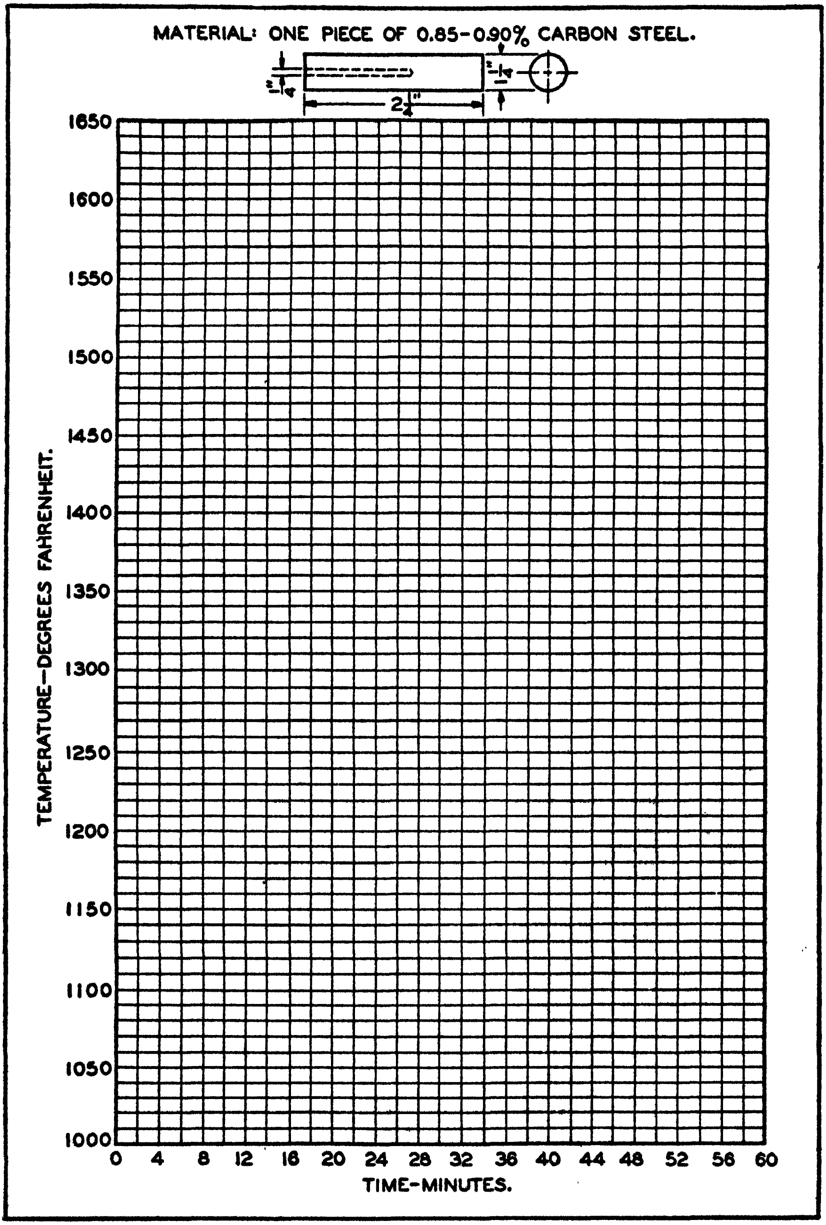


FIG. 121—HEATING AND COOLING CURVES

LABORATORY ASSIGNMENT 2

CRITICAL TEMPERATURES OF STEEL

Object: To determine the critical temperatures of a given steel.

Material: One piece of 1¼-inch round or octagonal carbon steel containing 0.85 to 0.90 per cent carbon.

Procedure: Place one thermocouple in the drilled hole in the piece of steel and another thermocouple in the furnace. Then supply heat to the furnace at a constant rate so as to obtain gradually increasing temperatures in the furnace. Record the temperatures of the piece of steel and the furnace atmosphere every two minutes. After the desired maximum temperature (about 1650 degrees F.) has been reached, shut off the heat and allow the furnace to cool. Record the temperatures every two minutes during cooling.

Record: Plot the temperatures obtained on both heating and cooling on the coordinates in Fig. 121. Note the temperatures at which the retardations in the heating and cooling occur. These are the critical temperatures of the steel and should be so designated on the curves in Fig. 121.

Reference: Chapter VI.

LABORATORY ASSIGNMENT 3

PROPERTIES OF HOT-WORKED STEEL AND COLD-WORKED STEEL

Object: To compare the properties of hot-worked steel with the properties of cold-worked steel having approximately the same chemical composition.

Material: Tensile-test specimens of ¾-inch hot-rolled steel and of ¾-inch cold-drawn (*S.A.E.* 1015) steel having a carbon content of 0.10 to 0.20 per cent.

Procedure: Make tensile tests of the hot-rolled steel and the cold-drawn steel, using specimens which have been machined to the standard dimensions given in Fig. 12. Determine the yield point, the tensile strength, the percentage elongation, and the reduction of area of these specimens. Also measure the hardness of the material by the Brinell, Rockwell, and scleroscope methods.

Record: The properties of the hot-rolled steel and the cold-drawn steel are to be recorded in the following outline·

TENSILE PROPERTIES

	Yield Point		Tensile Strength		Reduction of Area		Elongation	
	Load on Machine, Lb.	Lb. per Sq. In.	Load on Machine, Lb.	Lb. per Sq. In.	Final Dia., In	%	In.	%
Hot-Rolled Steel.....								
Cold-Drawn Steel.....								

HARDNESS MEASUREMENTS

	Brinell	Rockwell "B"	Scleroscope
Hot-Rolled Steel.....			
Cold-Drawn Steel....			

Reference: Chapter VI.

LABORATORY ASSIGNMENT 4

FRACTURE TEST OF STEEL

Object: To observe the effect of mechanical working and heat treatment upon the appearance of the fractured surface of steel.

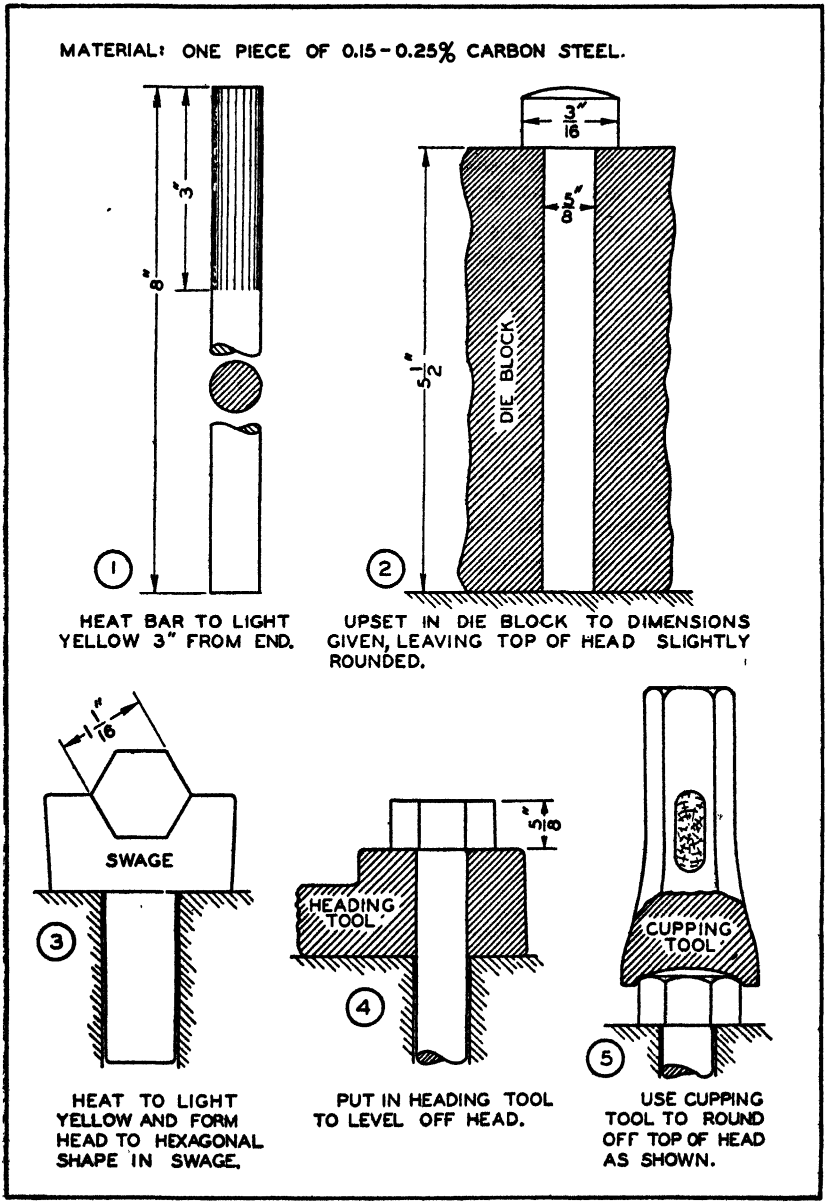
Material: One bar of ½-inch round or octagonal hot-rolled carbon steel containing 0.80 to 0.90 per cent carbon.

Procedure: Heat one end of the bar of steel in a forge fire to about 2000 degrees F. (light yellow color), and work to a rectangular section ¼ inch by ½ inch by about 4 inches long. While the metal is hot, make four notches on each side of the bar with the hardie so that pieces about ¾ inch in length can be broken from the bar. After working the steel to about 1400 degrees F. and cooling in the air to room temperature, break off sample 1. Then heat the remainder of the forged section of the bar to 2200 degrees F. (white heat) and cool in the air to room temperature. Break off sample 2. Again heat the end of the bar to about 2000 degrees F. and work the metal as it cools to about 1400 degrees F. Make other notches and break off sample 3. Heat the end of the bar to 1400 degrees F. and cool suddenly in water. Break off sample 4.

Record: In the following outline, record the appearance of the fractured surface of each sample.

Sample 1	
Sample 2	
Sample 3	
Sample 4	

Reference: Chapter VI.



MATERIAL: ONE PIECE OF 0.15-0.25% CARBON STEEL.

① HEAT BAR TO LIGHT YELLOW 3" FROM END.

② UPSET IN DIE BLOCK TO DIMENSIONS GIVEN, LEAVING TOP OF HEAD SLIGHTLY ROUNDED.

③ HEAT TO LIGHT YELLOW AND FORM HEAD TO HEXAGONAL SHAPE IN SWAGE.

④ PUT IN HEADING TOOL TO LEVEL OFF HEAD.

⑤ USE CUPPING TOOL TO ROUND OFF TOP OF HEAD AS SHOWN.

FIG. 122—HEAD ON BOLT FORMED BY UPSETTING OPERATION

LABORATORY ASSIGNMENT 5

UPSET-FORGING OPERATION—FORGING A HEAD ON A BOLT

Object: Practice in hot working steel by upsetting operation.

Material: One piece of $\frac{5}{8}$-inch round carbon steel containing 0.15 to 0.25 per cent carbon (*S.A.E.* 1020).

Procedure: Heat one end of the piece of steel to about 2200 degrees F. (white heat) and upset in a die block as shown in Fig. 122. Heat the upset portion of the steel and form the hexagonal shape in a swage on an anvil. Continue the hot working using both heading tool and swage, until the shape and dimensions given in Fig. 122 are obtained. In finishing the head on the bolt, use a cupping tool to round off the top of the head.

Notes: Many forgings are produced by an upsetting operation in which the cross section of a piece of metal is increased while its length is decreased. This operation requires that the metal be heated to a forging temperature only in a limited portion of the bar. Die blocks are generally used to hold the bar so that the upsetting will be confined to the desired section. Upsetting machines are used for the large production of bolts, rivets, gear blanks, gas-engine valves, and many other forged parts.

Reference: Chapter VII.

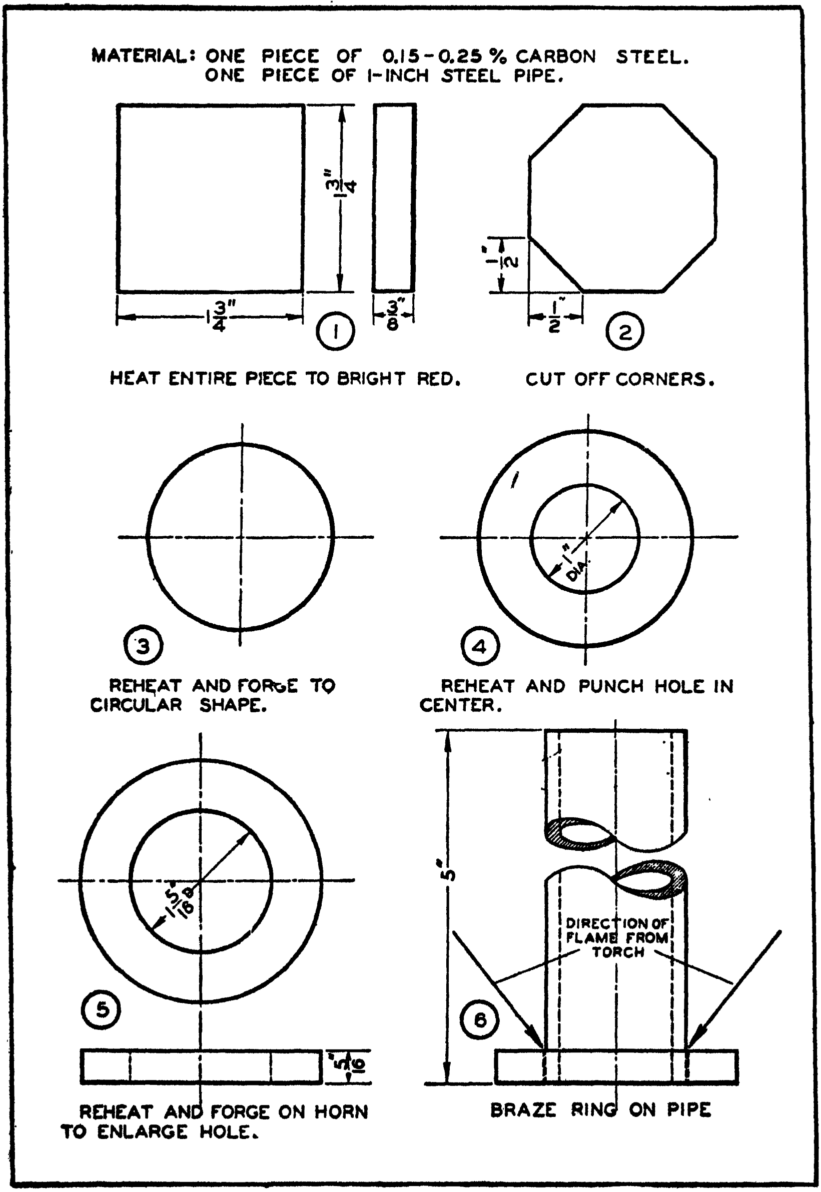

MATERIAL: ONE PIECE OF 0.15-0.25 % CARBON STEEL.
ONE PIECE OF 1-INCH STEEL PIPE.
1 3/4"
1 3/4"
3/8"
①
HEAT ENTIRE PIECE TO BRIGHT RED.
1/2"
1/2"
②
CUT OFF CORNERS.
③
REHEAT AND FORGE TO CIRCULAR SHAPE.
1" DIA.
④
REHEAT AND PUNCH HOLE IN CENTER.
1 5/16"
⑤
5/16"
REHEAT AND FORGE ON HORN TO ENLARGE HOLE.
5"
DIRECTION OF FLAME FROM TORCH
⑥
BRAZE RING ON PIPE

FIG. 123—FORGED RING BRAZED ON PIPE

LABORATORY ASSIGNMENT 6

FORGING A RING AND BRAZING RING ON PIPE

Object: Practice in hot working steel by punching and expanding operations. Practice in brazing.

Material: One piece of *S.A.E.* 1020 steel $\frac{3}{8}$ inch by $1\frac{3}{4}$ inches by $1\frac{3}{4}$ inches. One piece of 1-inch steel pipe 5 inches in length.

Forging Ring

Procedure: Heat the entire piece of steel in a forge fire to about 1800 degrees F. (bright yellow color), and cut off the corners with a hot chisel. Reheat the steel to about 2000 degrees F. and work the piece to the shape indicated in Fig. 123. Again heat the steel and punch a round hole in the center with a punch tapered from 1 inch to $\frac{1}{4}$ inch in diameter at the end. When punching a hole in hot steel, first drive the punch in about three-fourths of the thickness of the steel, then turn the piece over and drive the punch through from the opposite side. Again heat the steel and expand the hole to a diameter of $1\frac{5}{16}$ inches by hot working the metal on the horn of the anvil.

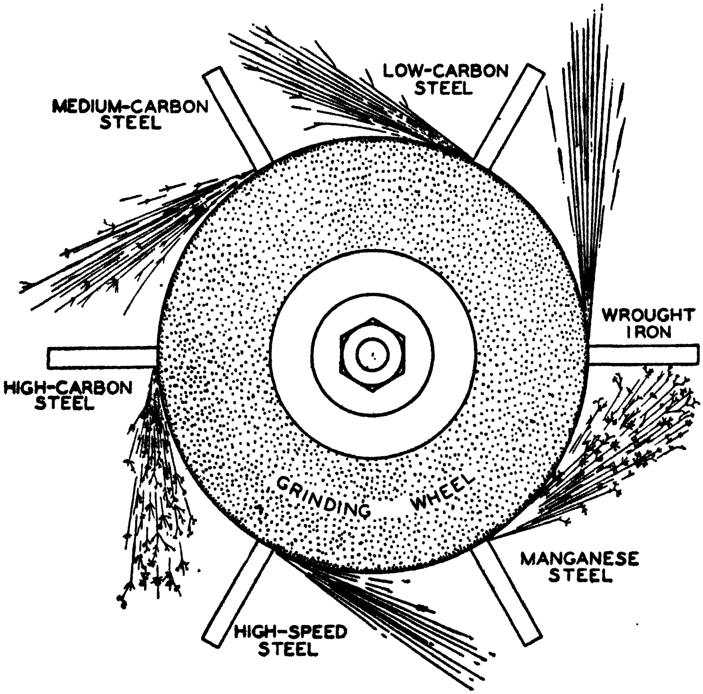
Brazing Ring on Pipe

File or grind the surfaces of the ring and pipe which come in contact to remove all scale. Assemble these parts as shown in Fig. 123. Heat the steel at the joint with a gas torch to about 1175 degrees F. (dark red color) and apply some flux (borax). The flux will melt at this temperature and will prevent the formation of oxides on the steel. Continue heating until the steel is at a temperature which will melt the brazing wire and cause it to flow into the joint. Allow the steel to cool undisturbed until the metal in the joint has completely solidified.

Testing

Grind the end of the ring and pipe so that the penetration of the brazing metal can be observed. Place the assembly in a fixture on a tensile testing machine so that loads can be applied to pull the pipe out of the ring. Record the maximum load required to cause failure of the pipe or the brazed joint.

Reference: Chapter XI.



WROUGHT IRON - GOLDEN-YELLOW STREAKS.

LOW-CARBON (.15-.25%) STEEL - BRIGHT STREAKS ARE DIVIDED OR FORKED BY SLIGHT EXPLOSIONS.

MEDIUM-CARBON (.40-.50 %) STEEL - EXPLOSIONS ARE MORE NUMEROUS AND MORE BRILLIANT.

HIGH-CARBON (.80-.90%) STEEL - EXPLOSIONS PRODUCE SHORT BUSHY CLUSTERS OF SPARKS BEGINNING CLOSE TO THE WHEEL.

HIGH-SPEED STEEL - DULL RED STREAKS WITHOUT EXPLOSIONS.

MANGANESE STEEL NUMEROUS EXPLOSIONS BRANCH OFF LIKE BUSHES.

FIG. 124—CHARACTERISTICS OF SPARKS

LABORATORY ASSIGNMENT 7

SPARK METHOD FOR SORTING STEELS

Object: To observe the characteristics of the sparks produced when specimens of iron and steel are brought in contact with a rapidly revolving grinding wheel, and to classify steels by the use of this method.

Materials: One piece each of wrought iron; carbon steel containing 0.15 to 0.25 per cent carbon; carbon steel containing 0.40 to 0.50 per cent carbon; carbon steel containing 0.80 to 0.90 per cent carbon; high-speed steel containing 0.70 per cent carbon, 18.00 per cent tungsten, 4 per cent chromium, and 1.00 per cent vanadium; manganese steel containing 1.00 to 1.30 per cent carbon and 11.00 to 13.00 per cent manganese. Six samples of steels for sorting.

Procedure: Hold each piece of metal in turn against a clean grinding wheel and note the color, shape, and other characteristics of the sparks produced. The explosions are due to the action of oxygen from the air upon the combustible constituents in the metal. Observe that pure iron does not oxidize as readily as a combination of iron and carbon. The higher the carbon content, the more explosions take place when particles of the steel are heated by friction against an abrasive wheel. With alloy steels such as high-speed steel and manganese steel, peculiar spark conditions are produced because of the influence of the special alloying elements in these steels.

Record: After becoming acquainted with the characteristic sparks from the metals of known composition, investigate the six unknown samples, and record in the space below the kind and class of each of these pieces of metal.

No.	Characteristics of Sparks	Material

Reference: Fig. 124.

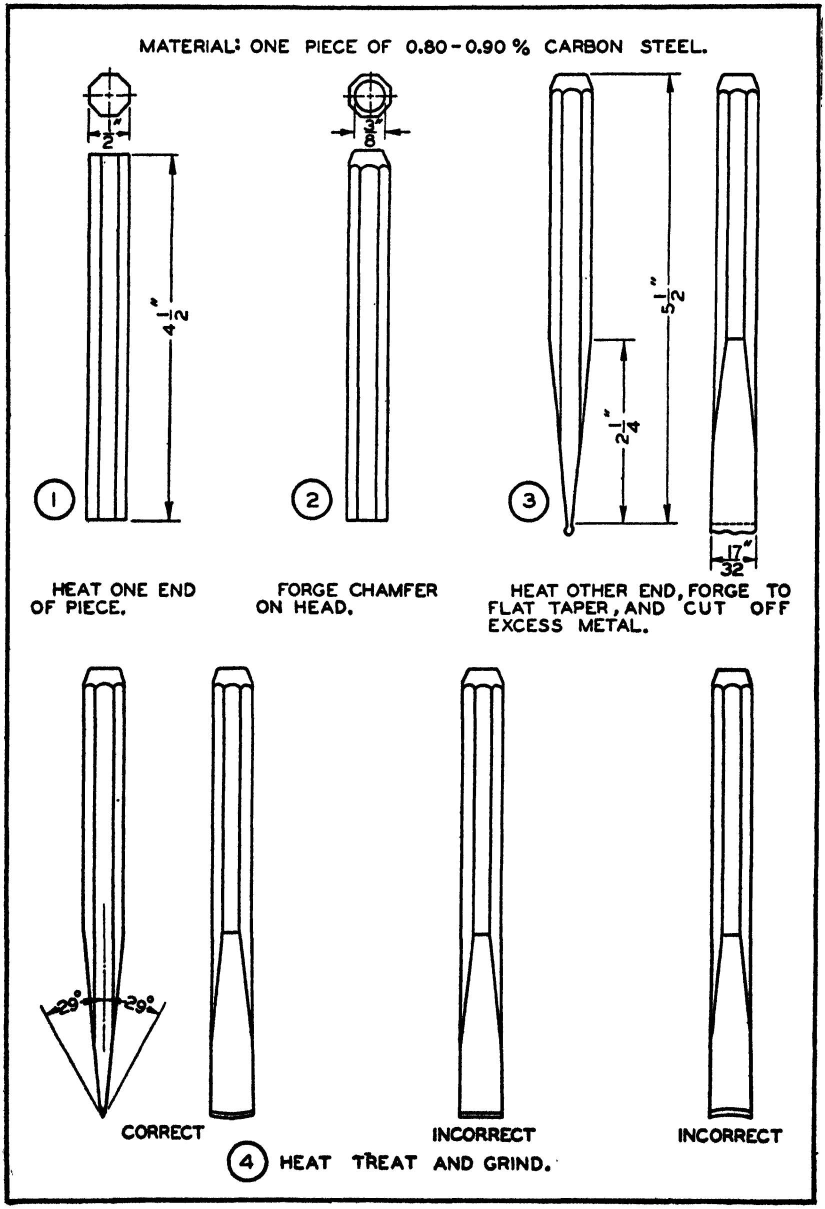


Fig. 125—Cold Chisel

LABORATORY ASSIGNMENT 8

FORGING AND HEAT TREATING A COLD CHISEL

Object: Practice in forging and heat treating carbon tool steel.

Material: One piece of $\frac{1}{2}$-inch octagonal carbon steel containing 0.80 to 0.90 cent carbon.

Forging

Procedure: Heat one end of the bar of steel to about 2000 degrees F. (light yellow color) and forge to the correct shape. The round edge of the anvil is used in drawing out the metal because this will have the least tendency to widen the piece. Draw out the metal slowly until it is $\frac{1}{32}$ inch thick at the end and tapers to $\frac{1}{2}$ inch thick at a distance of $2\frac{1}{2}$ inches from the end.

Hardening and Tempering

After the chisel has been forged to the desired shape, heat the cutting end to 1425 degrees F. (bright red color) for about 2 inches from the tapered end, and quench the steel vertically in cold water to a depth of about 1 inch, moving the chisel up and down during this operation. This motion of the chisel prevents a sharp line between the hardened area and the shank. Then use a stone to polish the end of the chisel which has been quenched, and allow the heat in the body of the chisel to reheat and temper the portion which has been quenched. When the color of the oxide at the cutting edge becomes purple, cool the hot end of the chisel in water to prevent further heating of the cutting edge.

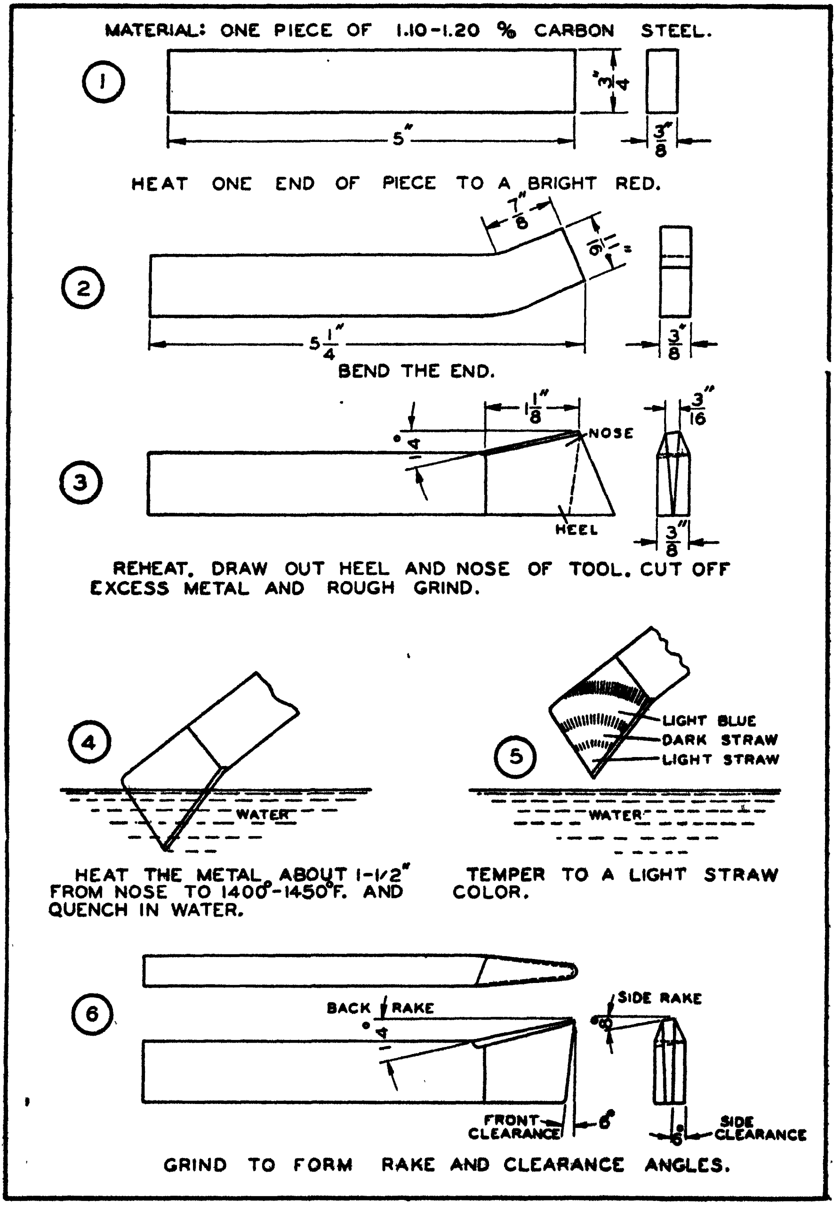
Grinding

Grind the cutting edge to the shape and angle shown in Fig. 125. Chisels which are used for general work have an angle of about 58 degrees. For cutting soft metals such as copper and brass, an angle of 35 to 45 degrees is most satisfactory. A chisel ground with a slightly convex edge will give longer service than the other shapes shown in Fig. 125. The corners of the cutting edge of a chisel are the weak points, and a convex edge gives the greatest protection to the corners.

Testing

After the cold chisel has been finished, it is used to cut a strip not less than 2 inches long on a cast-iron block.

Reference: Chapter VII and Chapter VIII.



MATERIAL: ONE PIECE OF 1.10-1.20 % CARBON STEEL.

HEAT ONE END OF PIECE TO A BRIGHT RED.

BEND THE END.

REHEAT. DRAW OUT HEEL AND NOSE OF TOOL. CUT OFF EXCESS METAL AND ROUGH GRIND.

HEAT THE METAL ABOUT 1-1/2" FROM NOSE TO 1400°-1450°F. AND QUENCH IN WATER.

TEMPER TO A LIGHT STRAW COLOR.

GRIND TO FORM RAKE AND CLEARANCE ANGLES.

FIG. 126—LATHE TOOL

LABORATORY ASSIGNMENT 9

FORGING AND HEAT TREATING A LATHE TOOL

Object: Practice in forging and heat treating carbon tool steel.

Material: One piece of $\frac{3}{8}$- by $\frac{3}{4}$-inch carbon steel containing 1.10 to 1.20 per cent carbon.

Procedure: Forge one end of the piece of steel into the shape of the round nose roughing tool shown in Fig. 126. Rough grind the edges of the tool to the dimensions given on the drawing. Heat treat this tool to obtain the desired properties. Then finish grind the tool to the angles shown in Fig. 126.

Test: Compare the cutting properties of this tool with a lathe tool made of high-speed steel, when cutting cast iron or hot-rolled steel.

Record: In the space below, state definitely the heat treatment to be used in hardening and tempering the lathe tool.

Reference: Chapter VII and Chapter VIII.

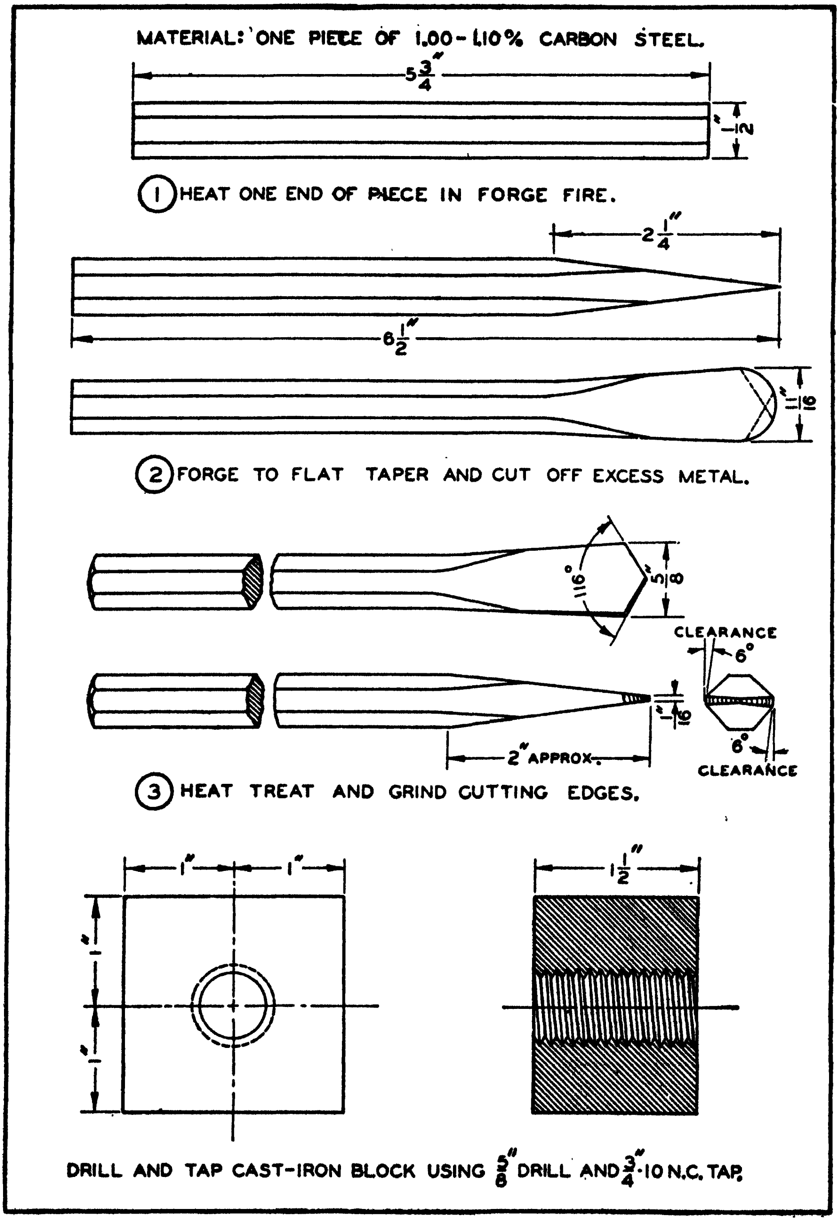

MATERIAL: ONE PIECE OF 1.00-1.10% CARBON STEEL.
5 3/4"
1/2"
① HEAT ONE END OF PIECE IN FORGE FIRE.
2 1/4"
6 1/2"
11/16"
② FORGE TO FLAT TAPER AND CUT OFF EXCESS METAL.
116°
5/8"
CLEARANCE
6°
1/16"
2" APPROX.
6°
CLEARANCE
③ HEAT TREAT AND GRIND CUTTING EDGES.
1"
1"
1"
1"
1 1/2"
DRILL AND TAP CAST-IRON BLOCK USING 5/8" DRILL AND 3/4"-10 N.C. TAP.

Fig. 127—Flat Drill

LABORATORY ASSIGNMENT 10

FORGING AND HEAT TREATING A FLAT DRILL

Object: Practice in forging, heat treating, grinding, drilling, and tapping.

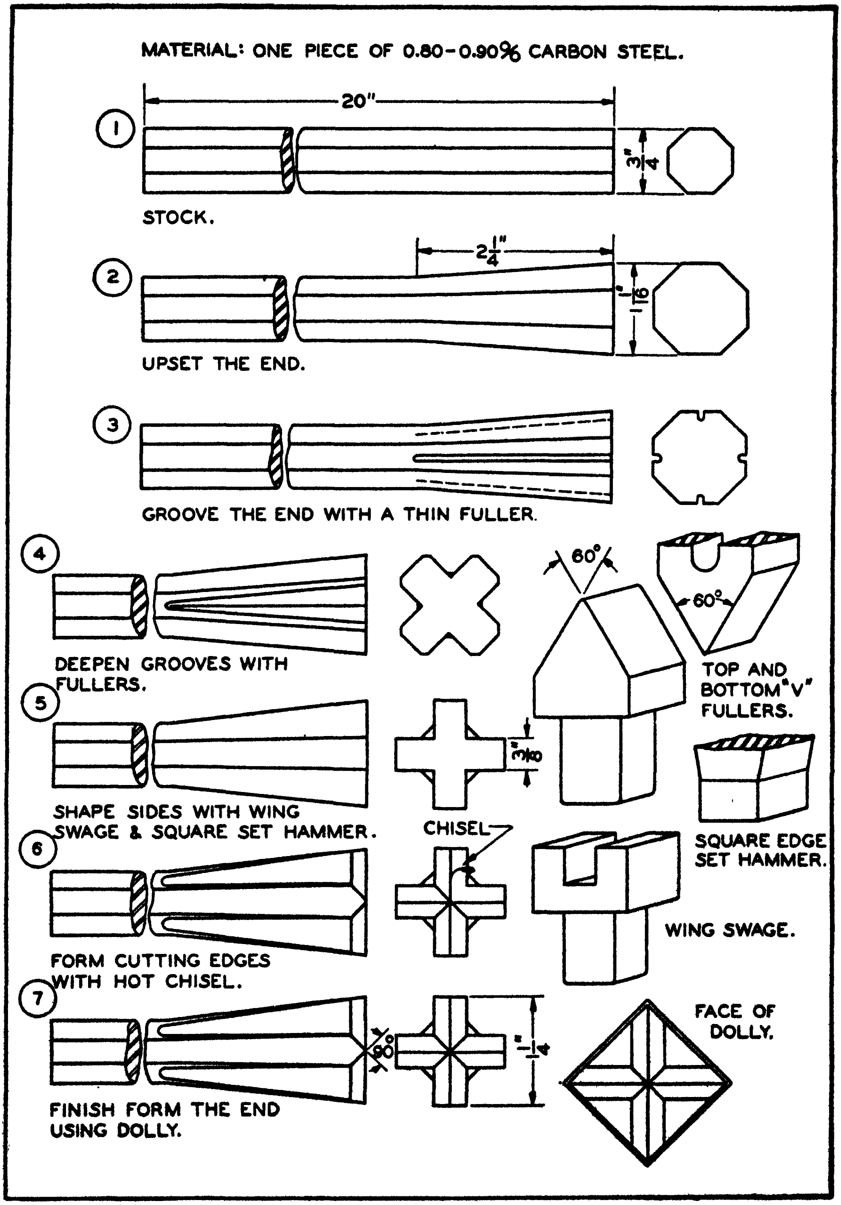
Material: One piece of $\frac{1}{2}$-inch octagonal carbon steel containing 1.00 to 1.10 per cent carbon and one block of cast iron.

Procedure: Heat one end of the piece of steel in a forge fire to 300 degrees above the upper critical temperature for this steel, and hot work the steel to the dimensions given in Fig. 127. After hardening and tempering the drill, grind the cutting edges to the angles shown on the drawing.

With this tool, drill a $\frac{5}{8}$-inch hole in a cast-iron block and cut threads on the inside of the hole with a $\frac{3}{4}$-inch tap.

Record: In the space below, state definitely the heat treatment to be used in hardening and tempering the flat drill.

Reference: Chapter VII and Chapter VIII.



MATERIAL: ONE PIECE OF 0.80-0.90% CARBON STEEL.

① STOCK.

② UPSET THE END.

③ GROOVE THE END WITH A THIN FULLER.

④ DEEPEN GROOVES WITH FULLERS.

⑤ SHAPE SIDES WITH WING SWAGE & SQUARE SET HAMMER.

⑥ FORM CUTTING EDGES WITH HOT CHISEL.

⑦ FINISH FORM THE END USING DOLLY.

Fig. 128—Forged Machine Drill

LABORATORY ASSIGNMENT 11

FORGING A MACHINE DRILL

Object: Practice in forging.

Material: One piece of ¾-inch octagonal carbon steel containing 0.80 to 0.90 per cent carbon.

Procedure: Heat one end of the piece of steel in a forge fire to about 2000 degrees F. (light yellow color), and upset the metal as shown in Fig. 128. Make small grooves along four sides of the bar with a thin fuller. After reheating the steel, form the wings with the top and bottom V-fullers. Turn the steel during this operation to obtain uniform depths in the fuller cuts. Again reheat the steel and forge the wings with a square set-hammer and swage. Then trim off the end of the drill and shape the cutting edges with a thin hot chisel. In order to obtain the desired shape of the end of the drill, it is driven while hot into a dolly.

The procedure for hardening and tempering the machine drill is the same as for the cold chisel (Assignment 8). The desired color of the oxide on tempering is a dark straw.

Reference: Chapter VII.

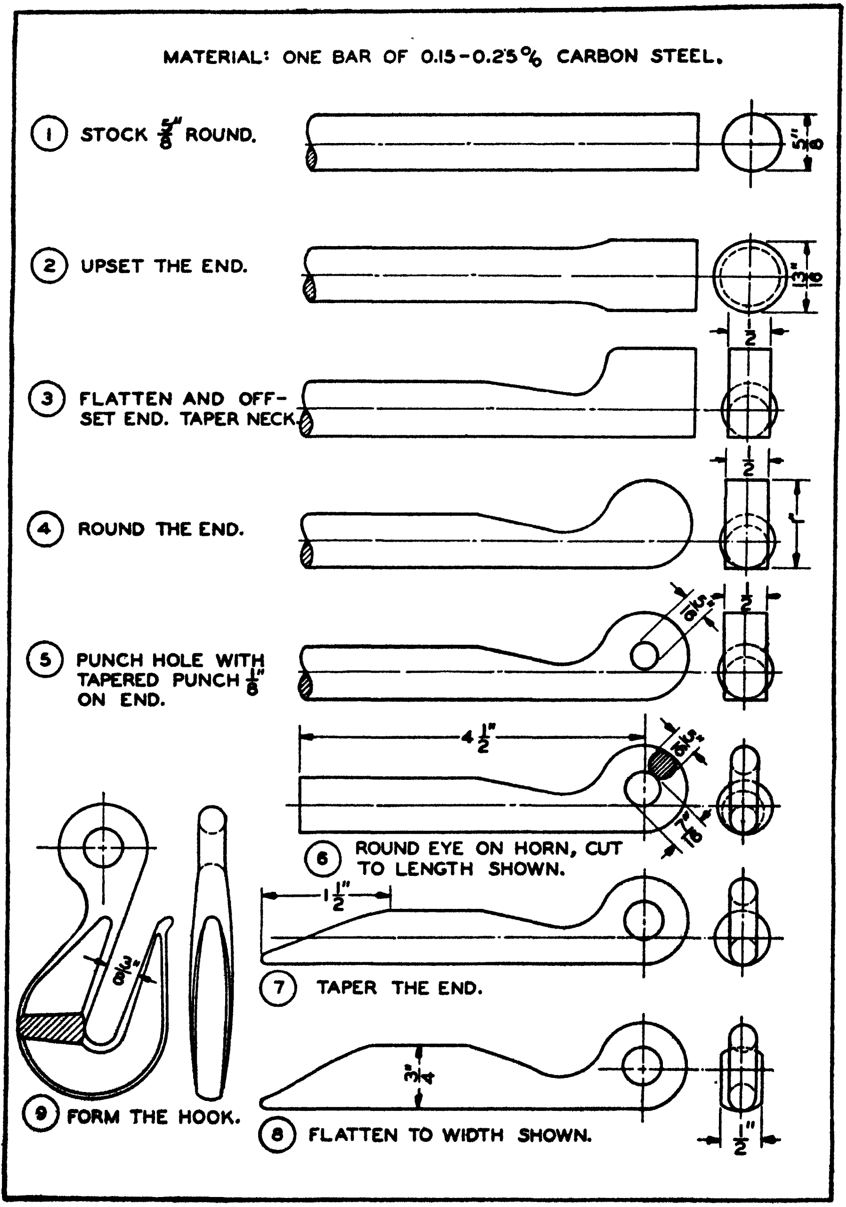

MATERIAL: ONE BAR OF 0.15–0.25% CARBON STEEL.
① STOCK 5/8" ROUND.
5/8"
② UPSET THE END.
13/16"
③ FLATTEN AND OFF-SET END. TAPER NECK.
1/2
④ ROUND THE END.
1/2
1"
⑤ PUNCH HOLE WITH TAPERED PUNCH 1/8" ON END.
5/8"
1/2
4 1/2"
5/8"
7/16"
⑥ ROUND EYE ON HORN, CUT TO LENGTH SHOWN.
1 1/2"
⑦ TAPER THE END.
3/4"
⑧ FLATTEN TO WIDTH SHOWN.
1/2"
5/8"
⑨ FORM THE HOOK.

Fig. 129—Forged Grab Hook

LABORATORY ASSIGNMENT 12

FORGING A GRAB HOOK

Object: Practice in forging.

Material: One bar of $\frac{5}{8}$-inch round *S.A.E.* 1020 steel.

Procedure: Heat one end of the bar of steel in a forge fire to about 2200 degrees F., and upset the steel for a short distance from the end as shown in Fig. 129. Again heat the metal to about 2200 degrees F. and flatten the upset portion on the face of the anvil. Off-set the end and taper the neck on the round edge of the anvil. After heating to 2000 degrees F., forge the end to a round shape by working in the corners. Again heat the steel and punch the hole in the center of the forged end. Round the inside edges of the hole over the horn of the anvil and enlarge the hole to the required size. Cut the forging from the bar to the length given on the drawing. Taper and flatten the metal to the specified shape and size, keeping one side straight.

Heat the entire piece to about 1700 degrees F., cool the ends in water, and form the hook over the horn of an anvil.

Reference: Chapter VII.

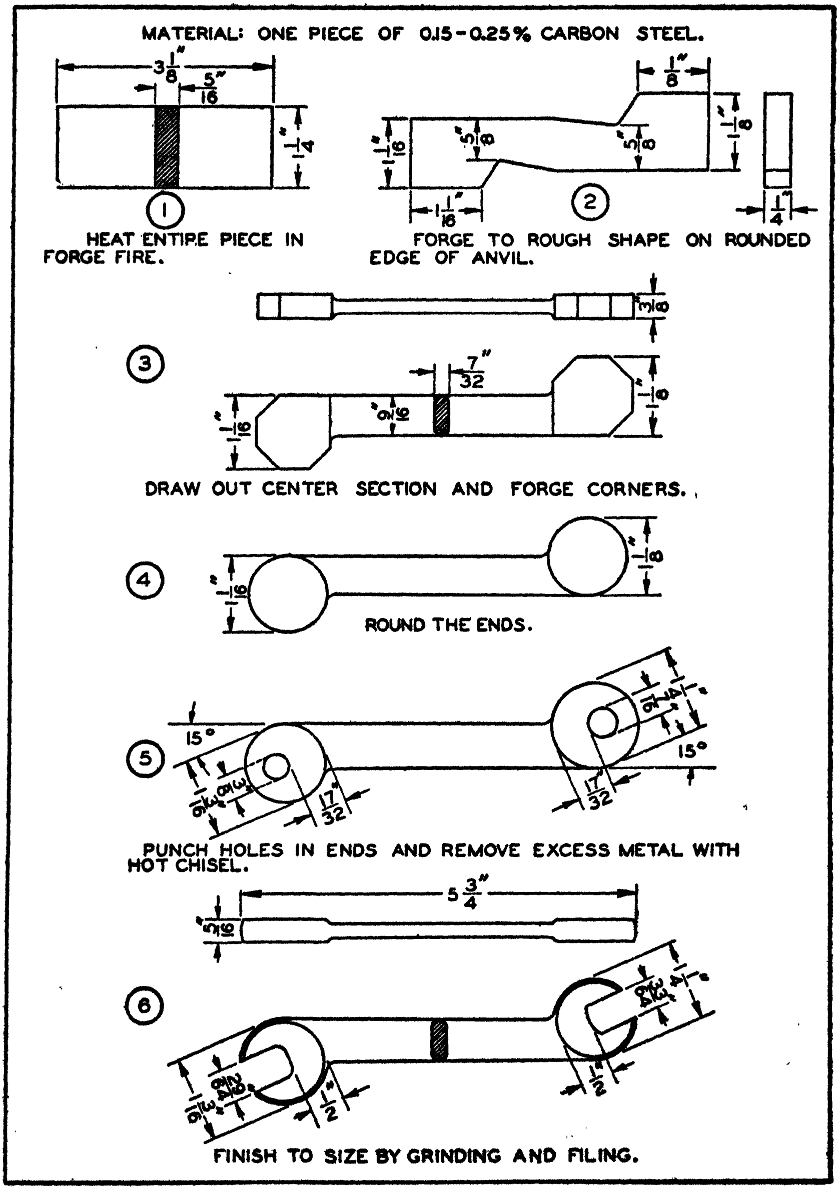

MATERIAL: ONE PIECE OF 0.15-0.25% CARBON STEEL.
3 1/8"
5/16"
1 1/4"
1
HEAT ENTIRE PIECE IN FORGE FIRE.
1/8"
1 1/16"
5/8"
5/8"
1 1/8"
1 1/16"
2
1/4"
FORGE TO ROUGH SHAPE ON ROUNDED EDGE OF ANVIL.
3/8
3
7/32"
5/16"
1 1/16"
1 1/8"
DRAW OUT CENTER SECTION AND FORGE CORNERS.
4
1 1/16"
1 1/8"
ROUND THE ENDS.
5
15°
9/32"
13/16"
17/32"
7/16"
1/4"
15°
17/32"
PUNCH HOLES IN ENDS AND REMOVE EXCESS METAL WITH HOT CHISEL.
5 3/4"
5/16"
6
29/64"
13/16"
1/2"
33/64"
1/4"
1/2"
FINISH TO SIZE BY GRINDING AND FILING.

FIG. 130—FORGED WRENCH

LABORATORY ASSIGNMENT 13

FORGING AND HEAT TREATING A WRENCH

Object: Practice in forging, grinding, filing, and heat treating.

Material: One piece of *S.A.E.* 1020 steel.

Procedure: Heat the piece of steel in a forge fire to about 2100 degrees F. (light yellow color), and work the metal to the shape and dimensions shown in Fig. 130. After punching the holes at the two ends, remove the extra metal with a hot chisel. Then work the metal to the approximate size, and finish the wrench by grinding and filing to the dimensions given on the drawing.

Suspend the wrench on a wire in a molten salt bath containing sodium cyanide. Heat the wrench for 15 minutes with the bath at 1500 to 1550 degrees F., and quench in cold water. With the aid of a file, note the hardness produced by this heat treatment.

Reference: Chapter VIII.

LABORATORY ASSIGNMENT 14

PROPERTIES OF HEAT-TREATED CARBON TOOL STEEL

Object: Practice in heat treating and hardness testing. To determine the hardness and microstructure of specimens of tool steel after different heat treatments.

Material: Carbon tool steel containing 1.10 to 1.20 per cent carbon.

Procedure: Nine pieces 2 inches long are cut from a bar of annealed, hot-rolled steel $\frac{3}{8}$ by $\frac{3}{4}$ inch in size. These pieces are machined on one side to a depth of about $\frac{1}{16}$ inch to remove any decarburized metal. After heat treating the steel as given in the instructions below, the pieces are carefully ground and polished for hardness measurements and microscopic observations. The results obtained are recorded in the following outline:

Piece No.	Heat Treatment	Hardness Values		Microstructure
		Rockwell "C"	Scleroscope	
1	Quenched in water from 1300° F.			
2	Quenched in water from 1425° F.			
3	Quenched in water from 1700° F.			
4	Quenched in oil from 1425° F.			
5	Cooled in air from 1425° F.			
6	Cooled in furnace from 1425° F.			
7	Same as 2 and tempered at 450° F.			
8	Same as 2 and tempered at 490° F.			
9	Same as 2 and tempered at 550° F.			

Reference: Chapter V.

LABORATORY ASSIGNMENT 15

PROPERTIES OF HEAT-TREATED CONSTRUCTIONAL STEELS

Object: Practice in heat treating and testing. To compare the properties of carbon steel and alloy steel in the annealed state, and after hardening and tempering.

Material: Tensile test specimens are made from constructional steels having the following compositions:

	Carbon Steel (*S.A.E.* ....)	*Alloy Steel* (*S.A.E.* ....)
Carbon.............	....	....
Manganese..........	....	....
Silicon..............	....	....
Sulphur (max.)......	....	....
Phosphorus (max.)...	....	....
Chromium..........	....	....
Nickel..............	....	....
Vanadium...........	....	....
Molybdenum........	....	....

Procedure: Heat treat the carbon steel as follows:

(A) Heat uniformly throughout at .... degrees F. and allow to cool slowly in the furnace.

(B) Heat uniformly throughout at .... degrees F. and quench in water. Temper at .... degrees F.

Heat treat the alloy steel as follows:

(C) Heat uniformly throughout at .... degrees F. and allow to cool slowly in the furnace.

(D) Heat uniformly throughout at .... degrees F. and quench in oil. Temper at .... degrees F.

Record: The physical properties of the steels after heat treatment are to be recorded in the following outline:

Specimen	Yield Point		Tensile Strength		Reduction of Area		Elongation	
	Load on Machine, Lb.	Lb. per Sq. In.	Load on Machine, Lb.	Lb. per Sq. In.	Final Dia., In.	%	In.	%
A								
B								
C								
D								

Reference: Chapter X.

LABORATORY ASSIGNMENT 16

CASE HARDENING

Object: To study the carburizing, hardening, and tempering operations of the case-hardening process.

Material: One piece of ½-inch round *S.A.E.* steel 2 inches long, and two pieces of *S.A.E.* steel each 3 inches long.

Procedure: The pieces of steel which have been carburized in a solid carburizing compound for 8 hours at 1700 degrees F. and cooled in the box are notched at intervals of one inch. They are then placed in a metal box with carburizer and heated to 1700 degrees F. for 45 minutes. The carburized parts are then treated as follows: Specimen No. 1 of *S.A.E.* steel is removed from the box and quenched in oil. Specimen No. 2 of *S.A.E.* steel is cooled in the box, reheated to 1450 degrees F., and quenched in water to refine the case. Specimen No. 3 of *S.A.E.* steel is cooled in the box, reheated to 1600 degrees F., and quenched in oil to refine the core. It is then heated to 1450 degrees F. and quenched in water to refine the case. Each piece is tempered at 350 degrees F.

Specimen	Hardness		Relative Toughness	Appearance of Fracture		Case Depth
	Rock. "C"	File		Case	Core	
1						
2						
3						

Reference: Chapter VIII.

LABORATORY ASSIGNMENT 17

CYANIDING

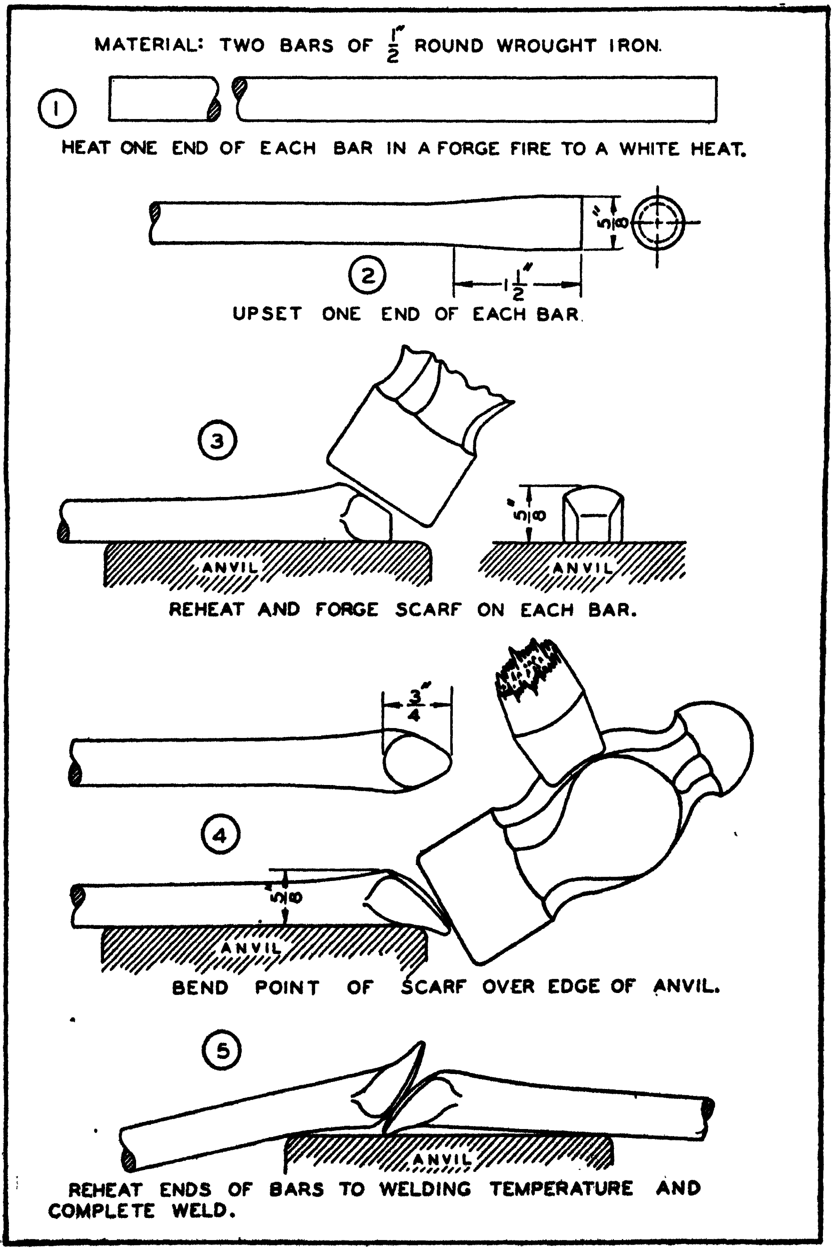
Object: To study the cyaniding process and to determine the physical properties of steel which has been cyanided.

Material: Carbon steel *S.A.E.* 1020, 4 × ½ × $\frac{1}{16}$ inches.

Procedure: The pieces of steel are immersed for 5 minutes and for 15 minutes in the molten cyanide bath maintained at 1550 degrees F., and are then quenched in water.

Time	File Hardness	Relative Toughness	Case Depth
5 Min.			
15 Min.			

Reference: Chapter VIII.



MATERIAL: TWO BARS OF $\frac{1}{2}''$ ROUND WROUGHT IRON.

① HEAT ONE END OF EACH BAR IN A FORGE FIRE TO A WHITE HEAT.

② UPSET ONE END OF EACH BAR.

③ REHEAT AND FORGE SCARF ON EACH BAR.

④ BEND POINT OF SCARF OVER EDGE OF ANVIL.

⑤ REHEAT ENDS OF BARS TO WELDING TEMPERATURE AND COMPLETE WELD.

Fig. 131—Forge Weld

LABORATORY ASSIGNMENT 18

FORGE WELDING

Object: Practice in forge welding.

Material: Two bars of $\frac{1}{2}$-inch round wrought iron.

Procedure: Heat one end of each bar in the forge fire to a white heat. Then upset the metal until the diameter is about $\frac{3}{4}$ inch for a distance of $1\frac{1}{4}$ inches back from the end. This is accomplished by placing the hot end of the bar against the face of the anvil and striking the cold end with a hammer.

Form a scarf on each bar by forging the material into the shape shown in Fig. 131. It is important that the surface of each scarf be made convex, to allow the liquid oxides to be squeezed out when the pieces are forced together during the welding operation.

Place the scarfed ends of the two bars in a forge fire with the scarfed surfaces down, and heat until a welding temperature (2650 degrees F., a sparkling white) is obtained. When both pieces have reached the desired welding temperature take them from the fire, and after striking them on the horn of the anvil to remove any loose scale, place them in the position for welding as shown in Fig. 131. A few rapid blows of the hammer will force any slag from the surfaces and unite the metals. If the edges of the scarfs are not completely welded, put the material back in the fire and work again after a welding heat is reached.

Test: In order to determine the strength of the weld, place the welded piece in a tensile testing machine and increase the load until failure occurs. Compare the maximum load on the welded piece with the maximum load on a piece of the same material which has not been welded.

Record: Maximum tensile load on welded bar............................

Maximum tensile load on bar not welded.........................

Reference: Chapter XI.

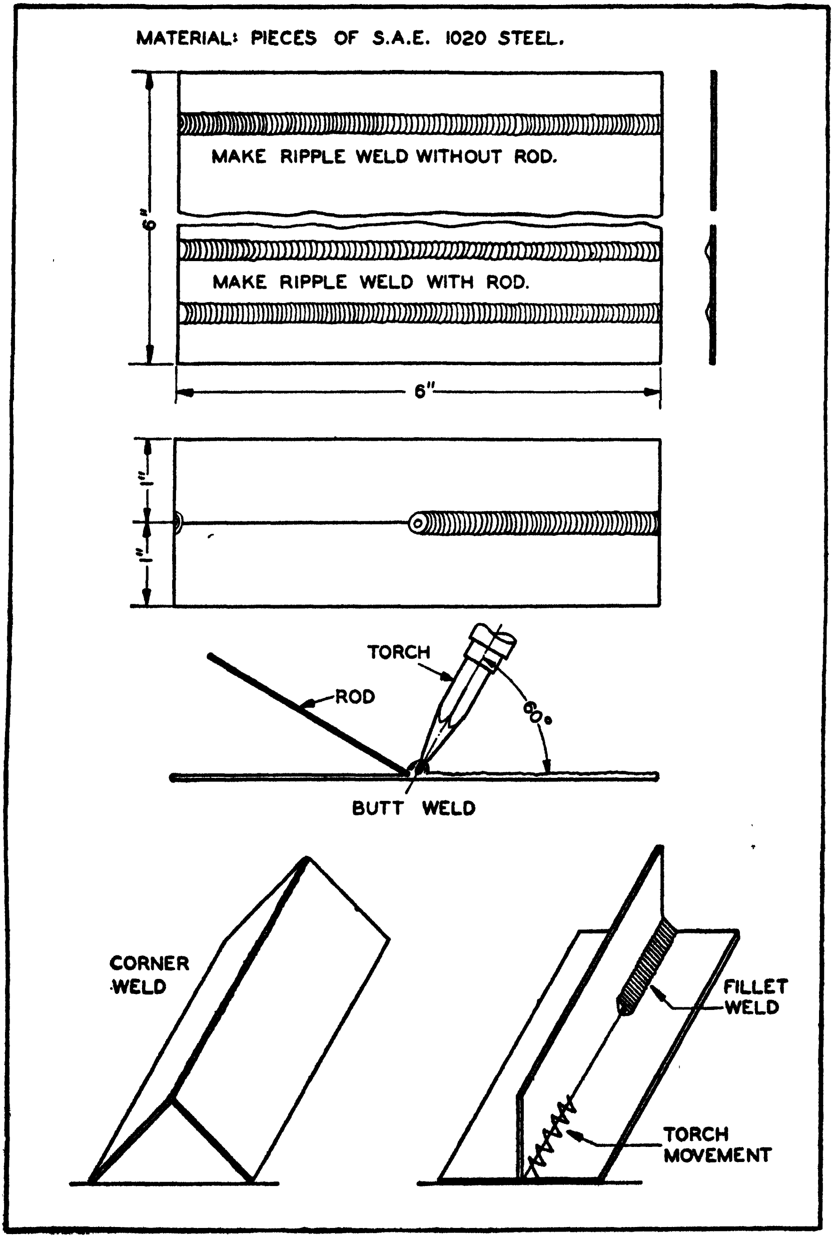

MATERIAL: PIECES OF S.A.E. 1020 STEEL.
MAKE RIPPLE WELD WITHOUT ROD.
6"
MAKE RIPPLE WELD WITH ROD.
6"
1"
1"
TORCH
ROD
60°
BUTT WELD
CORNER WELD
FILLET WELD
TORCH MOVEMENT

Fig. 132—Gas Welding Practice

LABORATORY ASSIGNMENT 19

GAS WELDING

Object: Practice in gas welding.

Material: Pieces of *S.A.E.* 1020 steel.
Welding rod (steel containing about 0.06 per cent carbon).

Procedure: Attach a No. 3 tip to the welding torch. Adjust the regulators so as to obtain a maximum pressure of 10 lb. per sq. in. for the oxygen gas and 5 lb. per sq. in. for the acetylene gas. Open the acetylene valve on the torch and ignite the flame. Then open the oxygen valve gradually. Adjust the acetylene valve until a neutral flame having the sharp, white inner cone is obtained. (Refer to Fig. 109.)

Make forward ripple welds on pieces of sheet steel without welding rod. Hold the torch at an angle of 60 degrees with the horizontal and pointing in the direction of travel. The inner cone of the flame should nearly touch the steel. Continue this practice until a straight row of uniform ripples is produced on the steel.

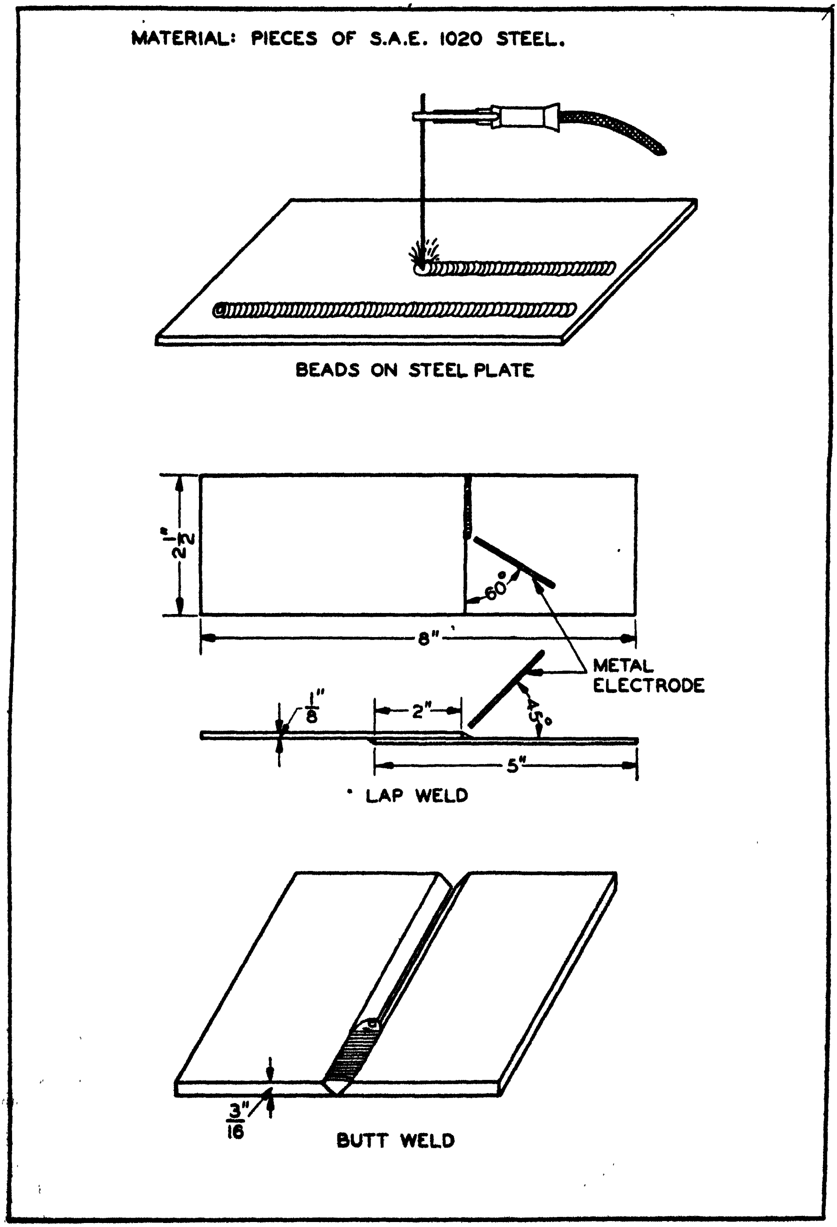
Make forward ripple welds on pieces of sheet steel with a welding rod. When starting a weld with the rod, a puddle of molten metal is first produced on the surface of the steel, and the end of the welding rod is placed in this puddle. As the welding proceeds, the rod is fed continuously into the molten metal.

After sufficient practice has been gained in making ripple welds on sheet steel, a butt weld is made with two pieces of 16-gage ($\frac{1}{16}$ inch in thickness) steel. Place the pieces together as shown in Fig. 132 and tack them by welding at the ends and center. Then make a ripple weld over the entire length of the joint.

Support two pieces of 16-gage steel at an angle and weld the top edge without using welding rod. Inspect this weld after the material has been hammered flat on an anvil.

Set up and tack a strip of sheet steel at right angles to the surface of a larger piece of the same material as shown in Fig. 132. Make a fillet weld on each side of the intersection.

Reference: Chapter XI.



MATERIAL: PIECES OF S.A.E. 1020 STEEL.

Fig. 133—Electric-Arc Welding Practice

LABORATORY ASSIGNMENT 20

ELECTRIC-ARC WELDING

Object: Practice in electric-arc welding.

Material: Pieces of *S.A.E.* 1020 steel.
Bare metal electrodes.

Procedure: Set the controls on the direct-current generator to deliver 125 amperes and 20 volts at the arc. Place a ⅛-inch bare electrode in the holder, and practice striking the arc and laying beads on sheet steel. Hold the electrode vertically over the point where the weld is to be started, but do not touch the work until the shield is in front of the face. In striking the arc, touch the end of the electrode lightly and quickly by a short swinging motion and withdraw the electrode about ⅛-inch from the work. Maintain this arc length by feeding the electrode down as the metal is deposited. Move the electrode along at a speed which will allow a pool of molten metal to be formed on the work for receiving the deposited metal.

After sufficient practice has been gained in holding the arc and depositing sound metal, make the lap weld shown in Fig. 133 and determine the strength of the joint by a tensile test or by bending. Additional practice is obtained by butt welding two pieces of heavy strip steel after the edges have been beveled as shown in Fig. 133.

In welding with bare electrodes, the shorter the arc that can be maintained with good fusion and penetration of the weld metal, the better the results. A long arc causes an increase in the oxidation of the deposited metal, produces poor fusion, and increases spatter, with the result that rough irregular deposits will be obtained. On the other hand, an arc which is too short causes poor fusion and overlap because of insufficient heat.

The penetration of the weld metal, as indicated by the depth of the crater in the weld, is caused by the fusion of the deposited metal with the parent metal. A satisfactory bead will penetrate to a reasonable depth to insure good fusion.

Precautions: Never strike an arc, even for an instant, unless the eyes of everyone in the vicinity are protected from the rays. While no permanent injury results from exposure to the rays of the arc, such exposures may cause extreme pain if the eyes or skin are exposed frequently, even for short periods of time.

When the electrode sticks to the steel plate, it should be broken loose very quickly with a rapid twisting or bending motion. If it is not loosened at once, remove the electrode holder, allow the electrode to cool, and then break it off.

Reference: Chapter XI.

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